# Testing Procedure

# Repeatability is KING !

**In order to repeat any given test at some time in the future, it is essential that all variables are noted, for example:**

- Engine build specification
- Ignition and injection timing
- Type of fuel, oil and coolant
- Position of sensors on the engine and within the cell

It will be impossible to replicate tests at some time in the future if one does not have full records of engine build, cam timing, ignition and injection timing, compression ratio, fuel,oil and coolant used.

# Calibration Equipment Identification

Where possible all critical equipment shall be tagged or labelled with the serial number, frequency of calibration and calibration status shown on the tag or label.

# Engine Tests used within the testing industry:

- **Durability (Design Validation Test)** Within this group is;
- Steady load and speed operation
- Load cycling
- Speed cycling
- Thermal shock cycling
- Component development
- Vehicle cycle simulation

# Performance, Within this group is;

- · Power curves
- · Governor curves
- · Lubrication oil consumption
- · Flow measurements
- · Heat balance
- Emissions measurement
  –

# Lubricants & Fuels Within this group is;

- Automotive lubricants
- Marine lubricants
- Black sludge formation
- Intake valve deposits
- Combustion chamber deposits

# Specialised investigations and testing

## Within this group is:

- Rig testing (bearings, antifreeze, erosion etc.)
- Simulated or environmental testing
- Photo elastic stress measurements
- Strain gauge testing
- Flywheel burst testing

# Exhaust system testing
## Within this group is:

- Vehicle cycle simulation
- Steady state

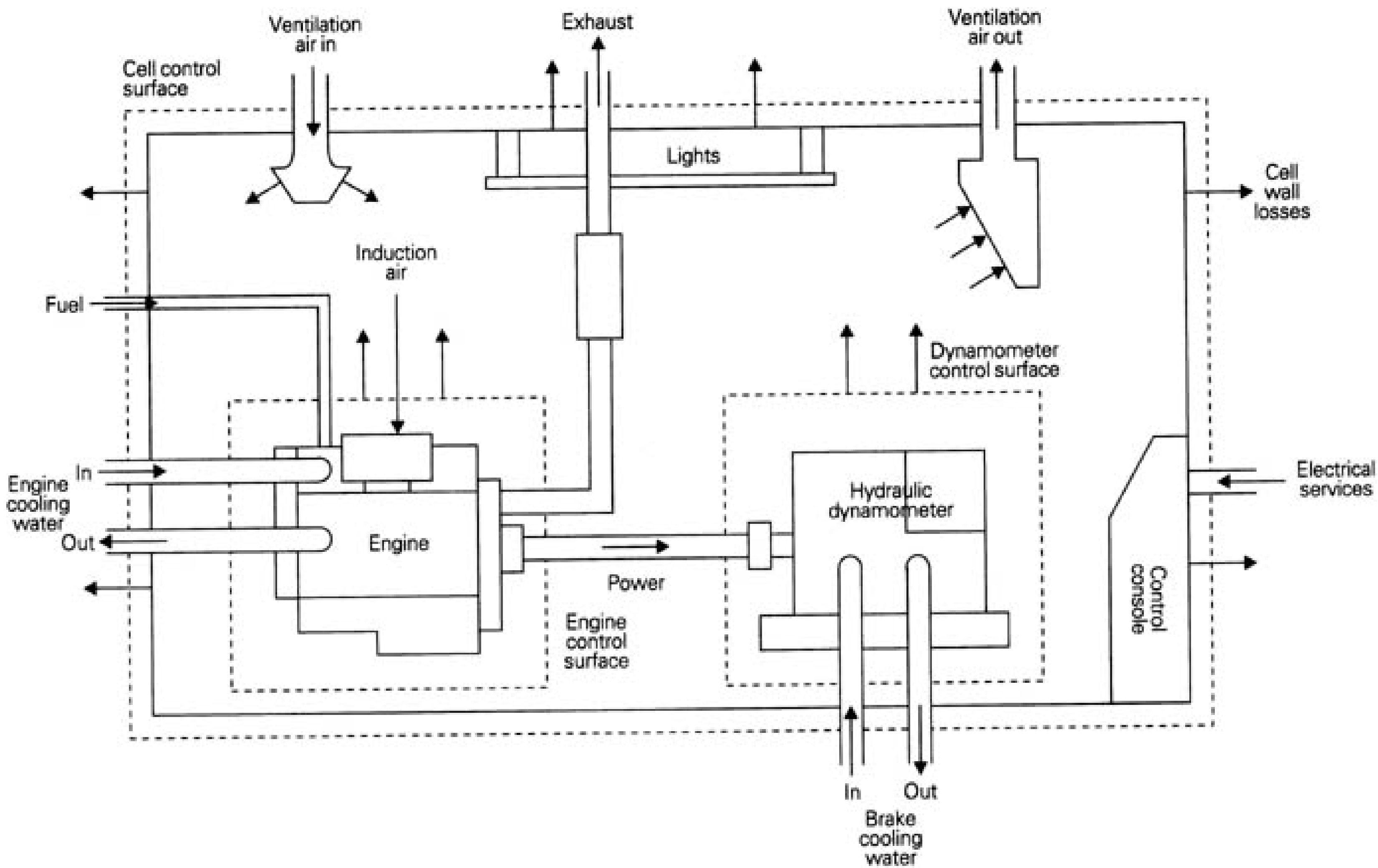
# Catalyst ageing Within this group is:

- Vehicle cycle simulation
- Steady state
- Accelerated ageing
- Light off efficiency tests
- Sulphate release tests

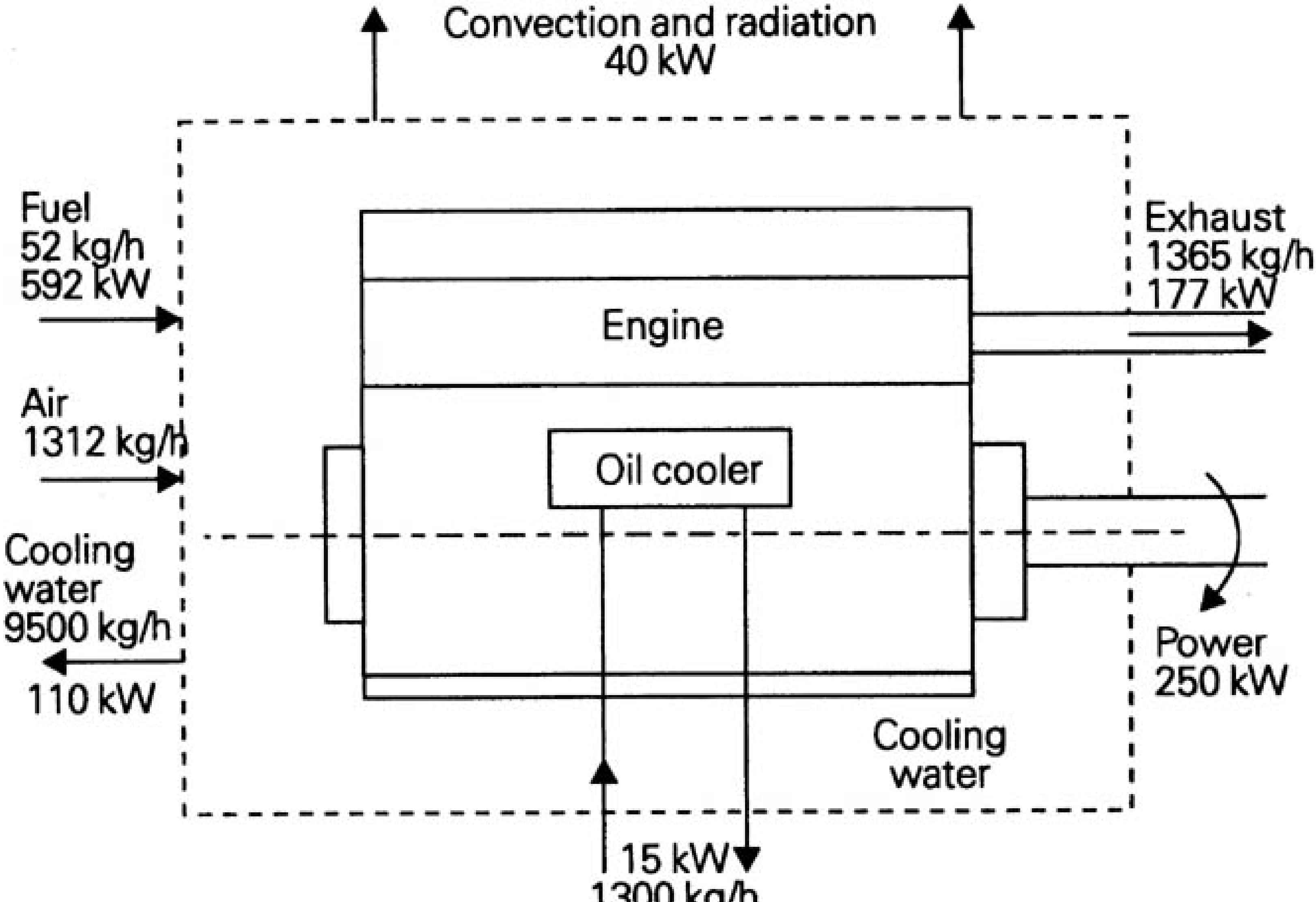
# Transient testing

- Fully transient tests and indeed automatic mapping software programmes are disciplines worthy of additional study, however, in order to glean the maximum useful repeatable data from all forms of transient testing, it is essential to have a full understanding and experience of steady state test types. Mathematical modelling of engine functions is an essential element in the design and development of new engine types. It is the accurate cross correlation of modelled data with actual running data that enables the leading manufacturers to rapidly move ahead of the opposition and obtain clear market gains.

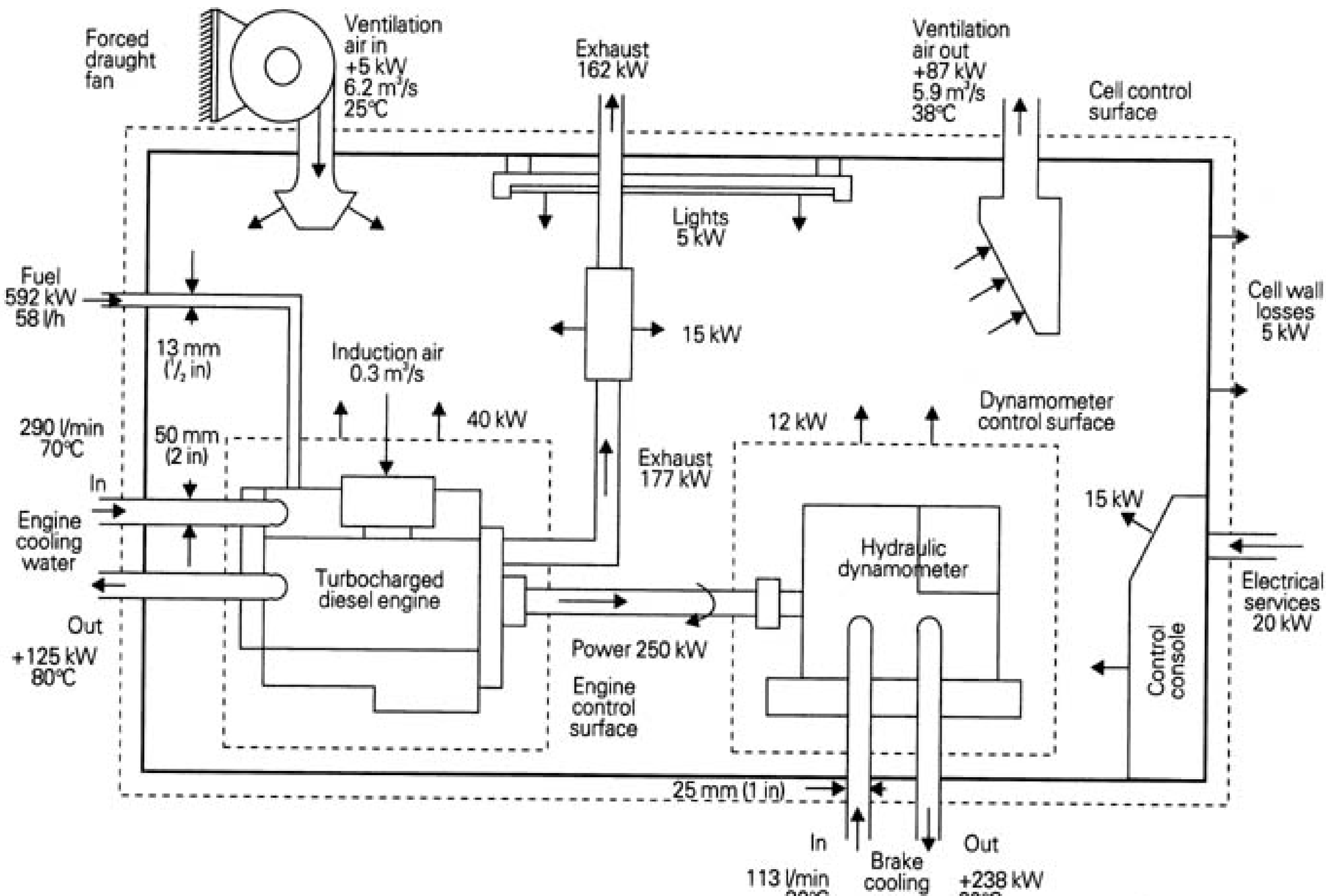
# Services in and out of the test cell



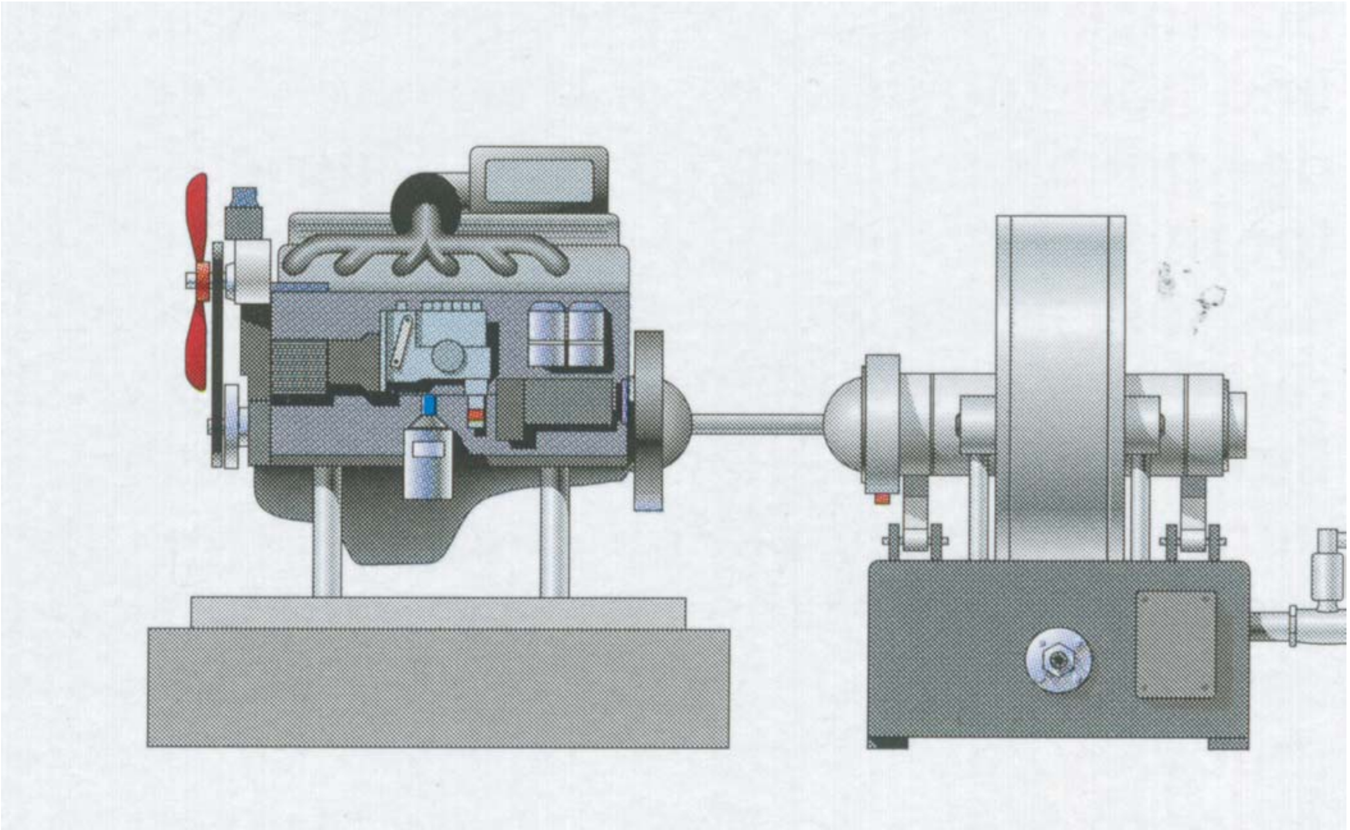
# Energy balance



# Energy balance, the test cell as a unique system



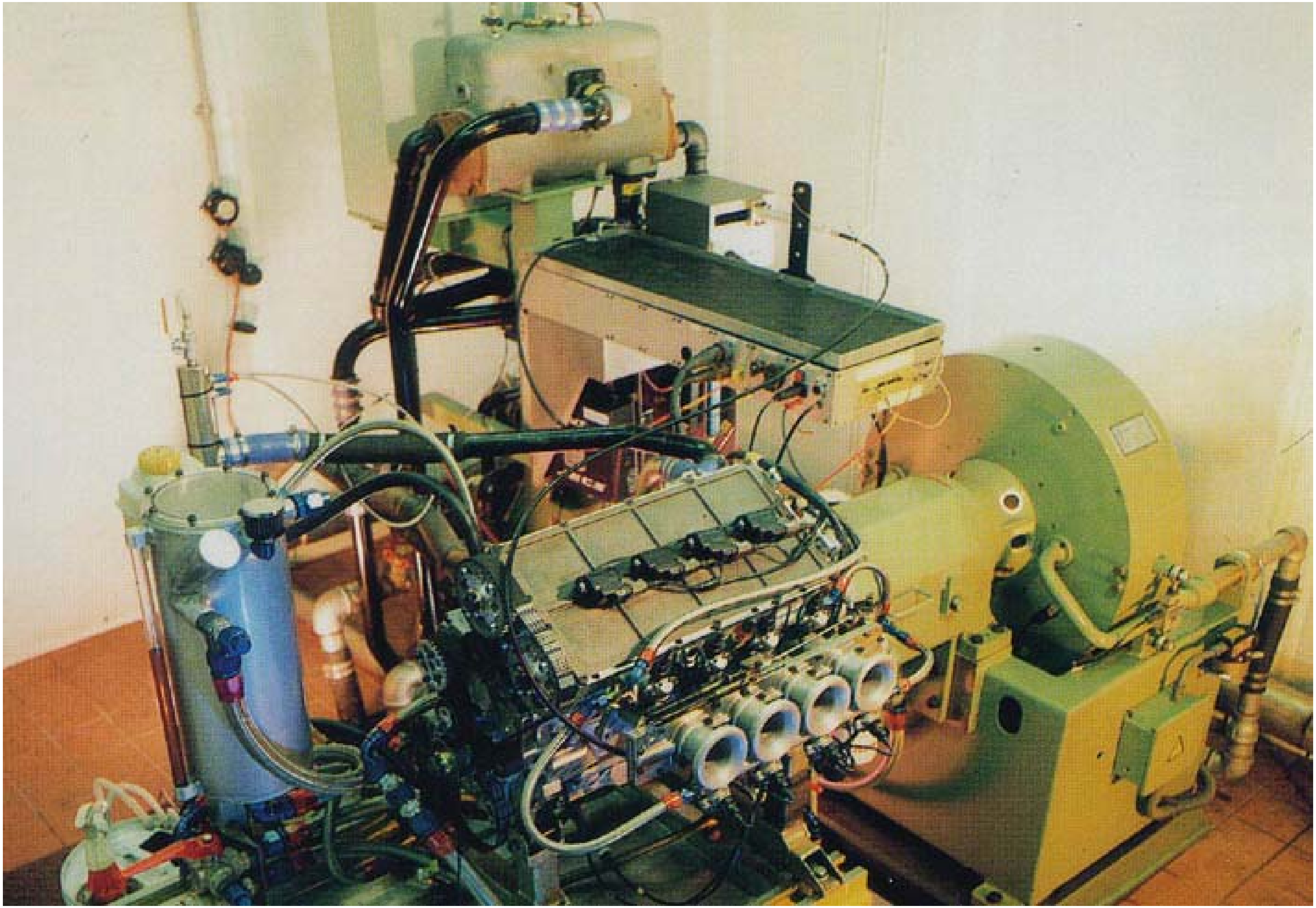
# Typical test arrangement



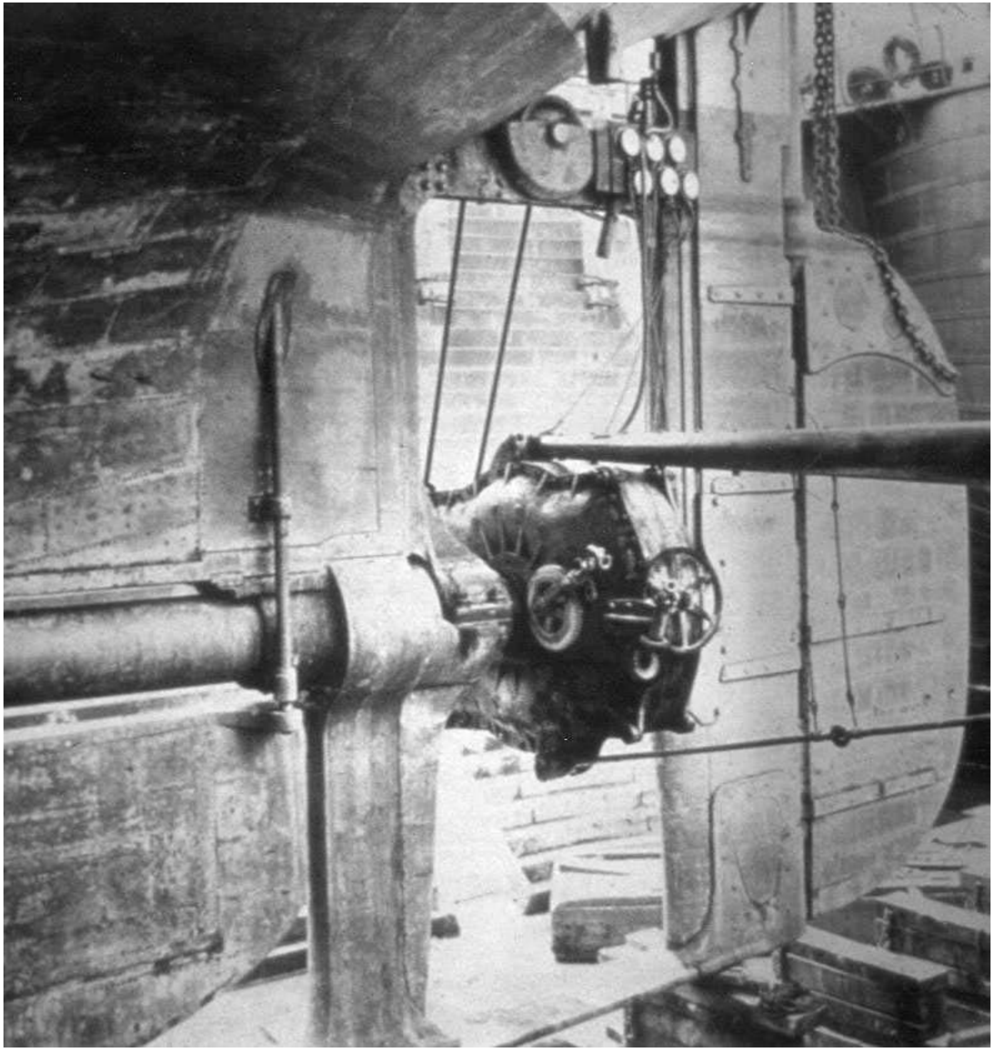
# Installation within the test cell

- Pallet
- QA ~ Instructions
- Documentation
- Items used
- Alignment
- Drive shafts
- Containment

# Installation in the test cell

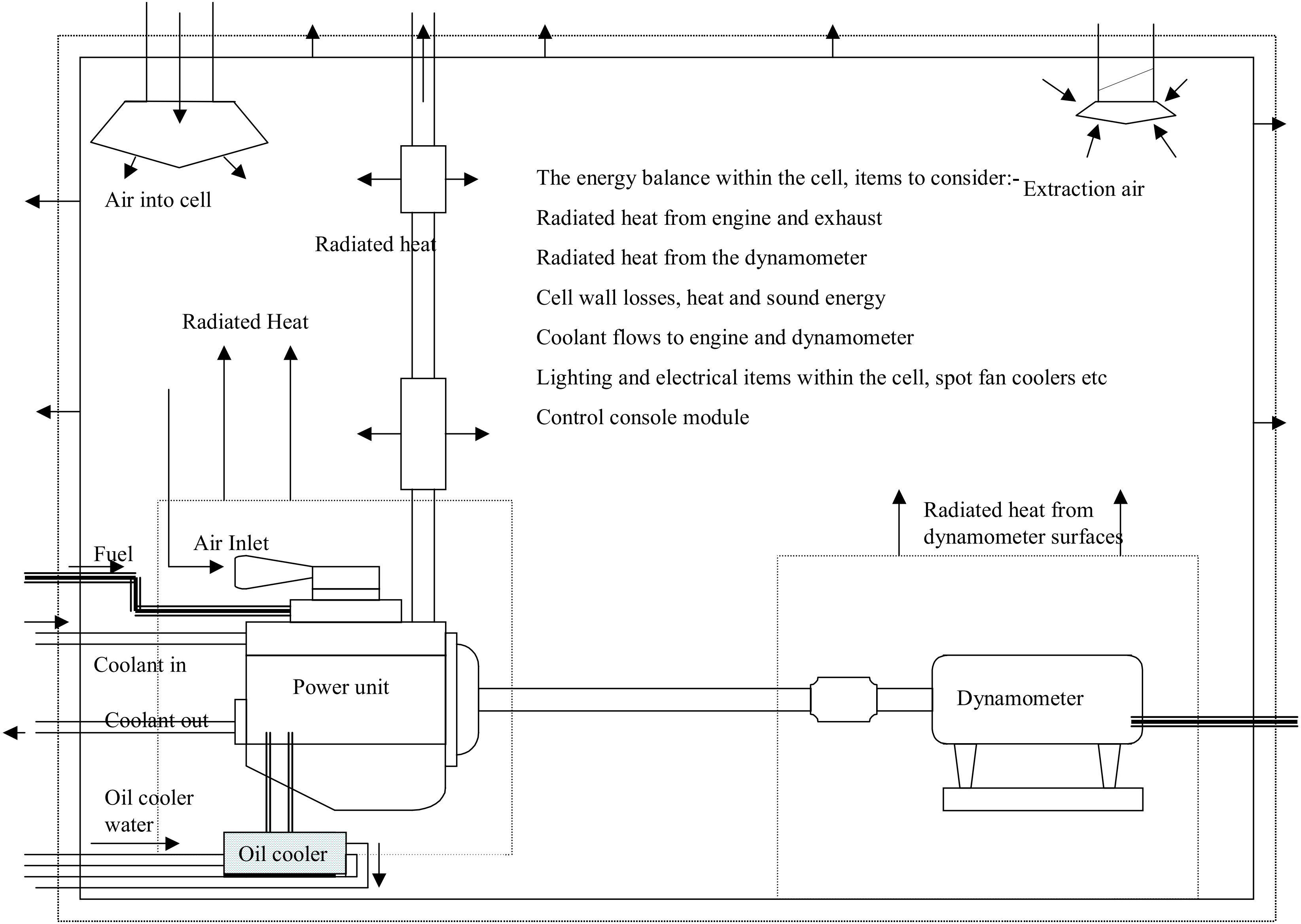


# First Froude Dynamometer



**William Froude**

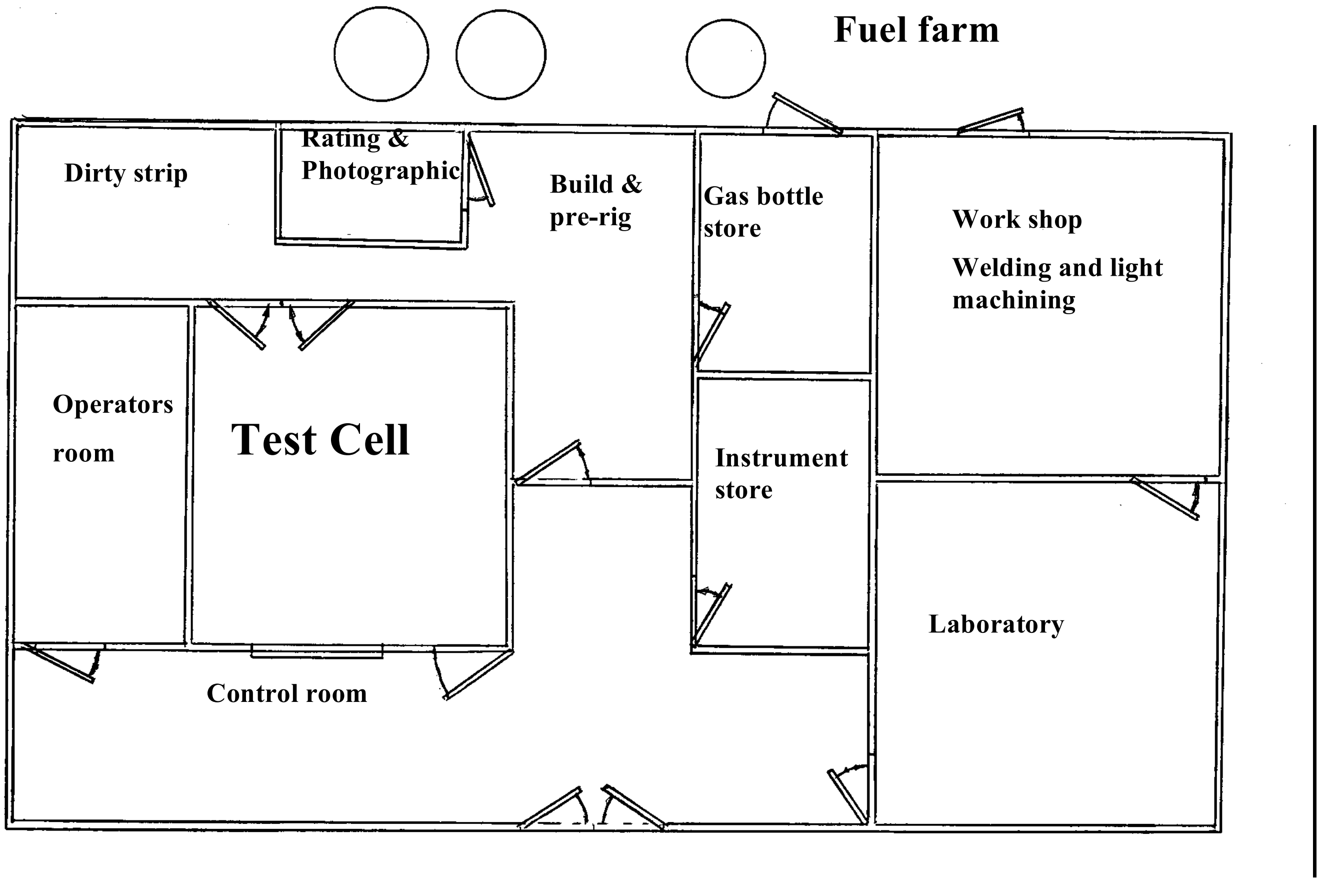
# Typical test cell

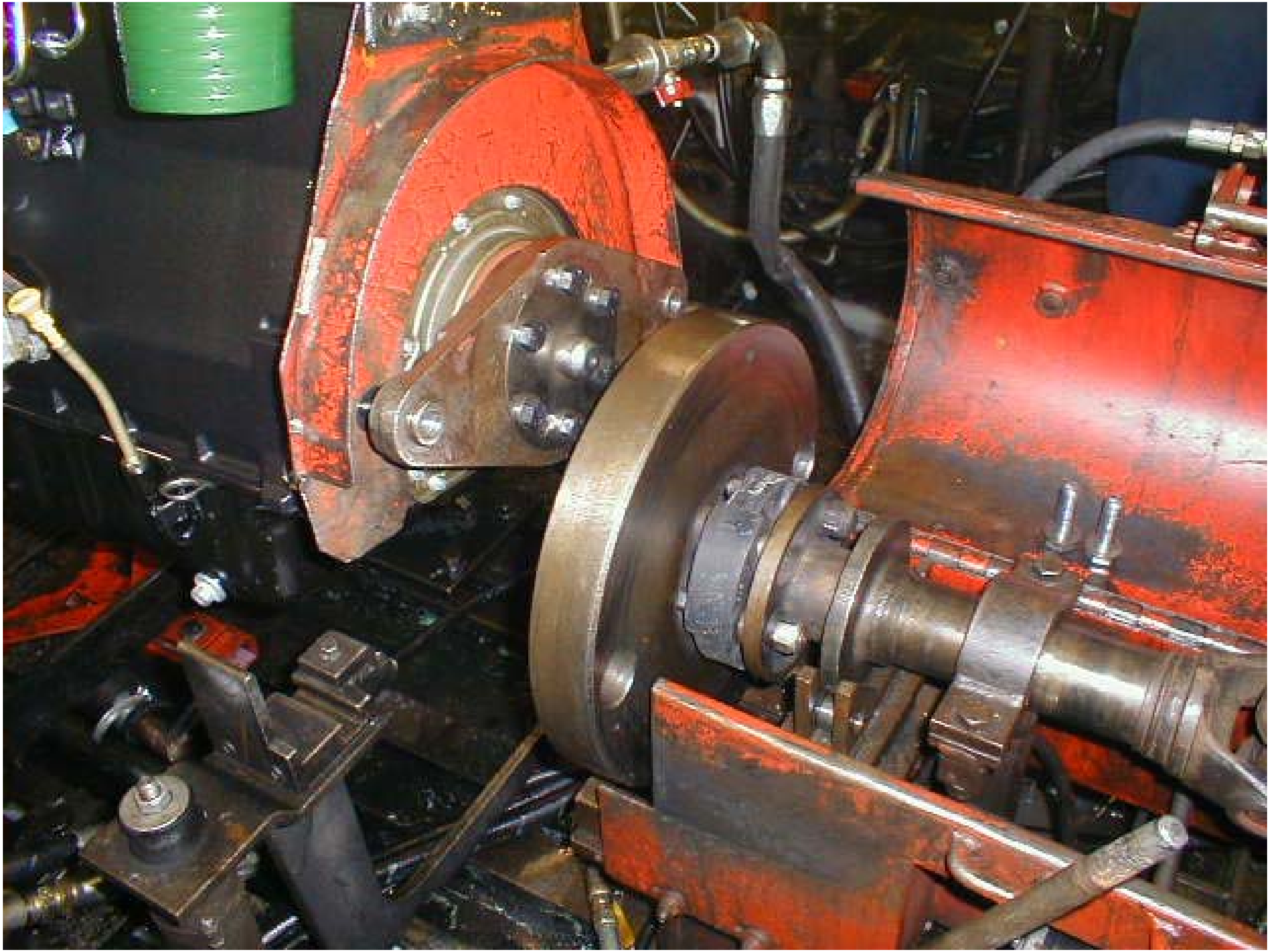


# Energy balance

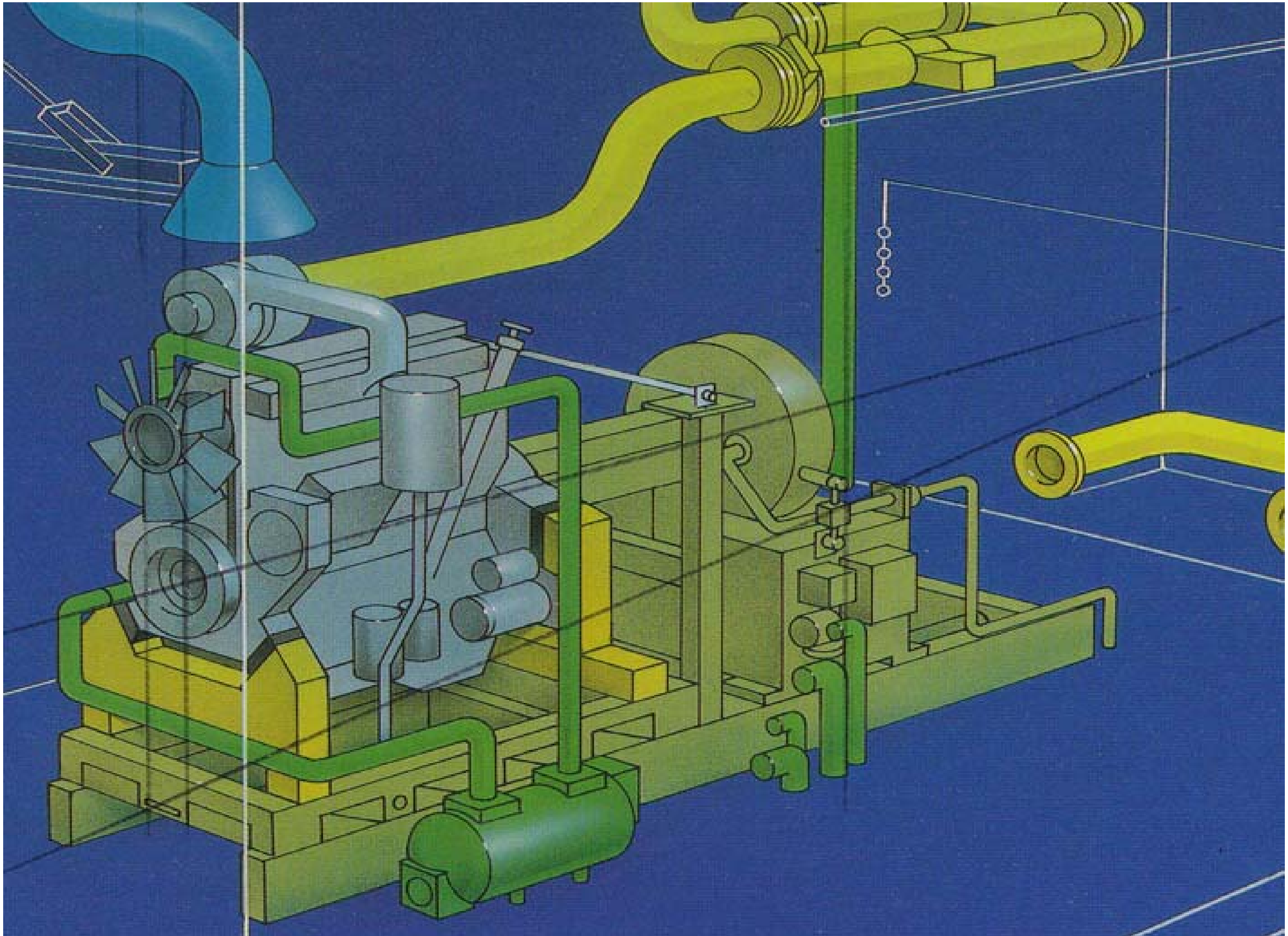
**The energy balance of a 75kW turbocharged diesel engine is as follows:**

| **In** | | **Out** | |
|---|---|---|---|
| Fuel | 176.53kW | Power | 75kW (42.2%) |
| | | Heat to coolant | 33kW(18.6%) |
| | | Heat to oil | 4.5kW (2.5%) |
| | | Heat to exhaust | 53.1 kW (29.9%) |
| | | Convection & radiation | 11kW (6.8%) |
| **TOTALS** | **176.53kW** | | **176.53kW** |


Fuel farm
Dirty strip
Rating &
Photographic
Build &
pre-rig
Gas bottle
store
Work shop
Welding and light
machining
Operators
room
Test Cell
Instrument
store
Laboratory
Control room



# Scribed and plumb Lines

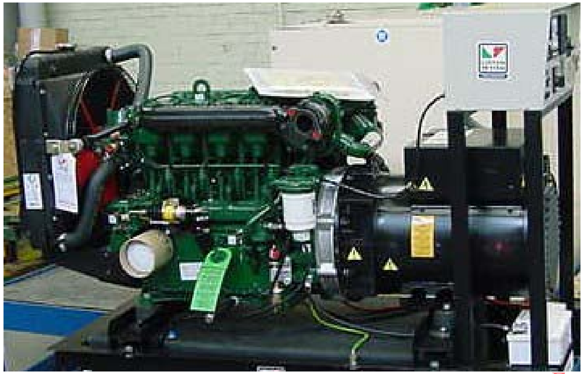


# Test Types

- Durability
- Performance
- Lubricant and Fuel
- Exhaust systems
- Catalyst ageing
- Specialist investigations

# Types of Validation Test

- **Tests should ideally replicate in service life**
- It is necessary to accelerate the testing
- A representative cycle for all engines is not possible
- There are however a number of discrete running conditions which give the most arduous conditions for key components
- Some applications are simple, for example off highway generating set applications



Lister Petter

# Specifying Validation tests

**Three aspects need to be considered**

I. Verify that wear will not prevent the designed life being achieved

II. Verify that mechanical fatigue failure does not occur within the designed life

III. Verify that thermal fatigue failure does not occur within the designed life

# Validation duty cycles

- To cater for the majority of cases and to ensure that components are assessed under the most severe operating conditions, it is usual to specify a test cycle that incorporates one the four extreme conditions we discussed earlier

- The engine build and installation on the test bench should replicate that of the vehicle

# Engineering limits of materials

- **The endurance limit for typical engineering materials is quoted as being between $10^6$ and $10^7$ cycles**
- In a four stroke engine, a complete load cycle occurs once every two revolutions ( 720° )
- $10^7$ cycles would occur after 166 running hours at a rated speed of 2000 rev/min.

**The first jet airliner, the Comet (shown below), was launched in Britain in 1949.**

$10^7$ low amplitude cycles and the wings fell off in 1950 !

# Optica

Mike Hewland engine based on F1 go cart application. Propellor came adrift killing two policemen.

Material fatigue problem.

# Designing a test based upon mechanical fatigue

- **The test cycle for a 1000 hour test would be:**
- Test cycles
  - 2 x 10 @ full load and speed
  - 4 x $10^6$@ idle
  - 1.6x $10^7$ @ maximum torque
  - 1.065x$10^7$ governor run out speed
  - A total of 5x $10^7$ cycles
  - This test would demonstrate a high degree of confidence with respect to mechanical fatigue

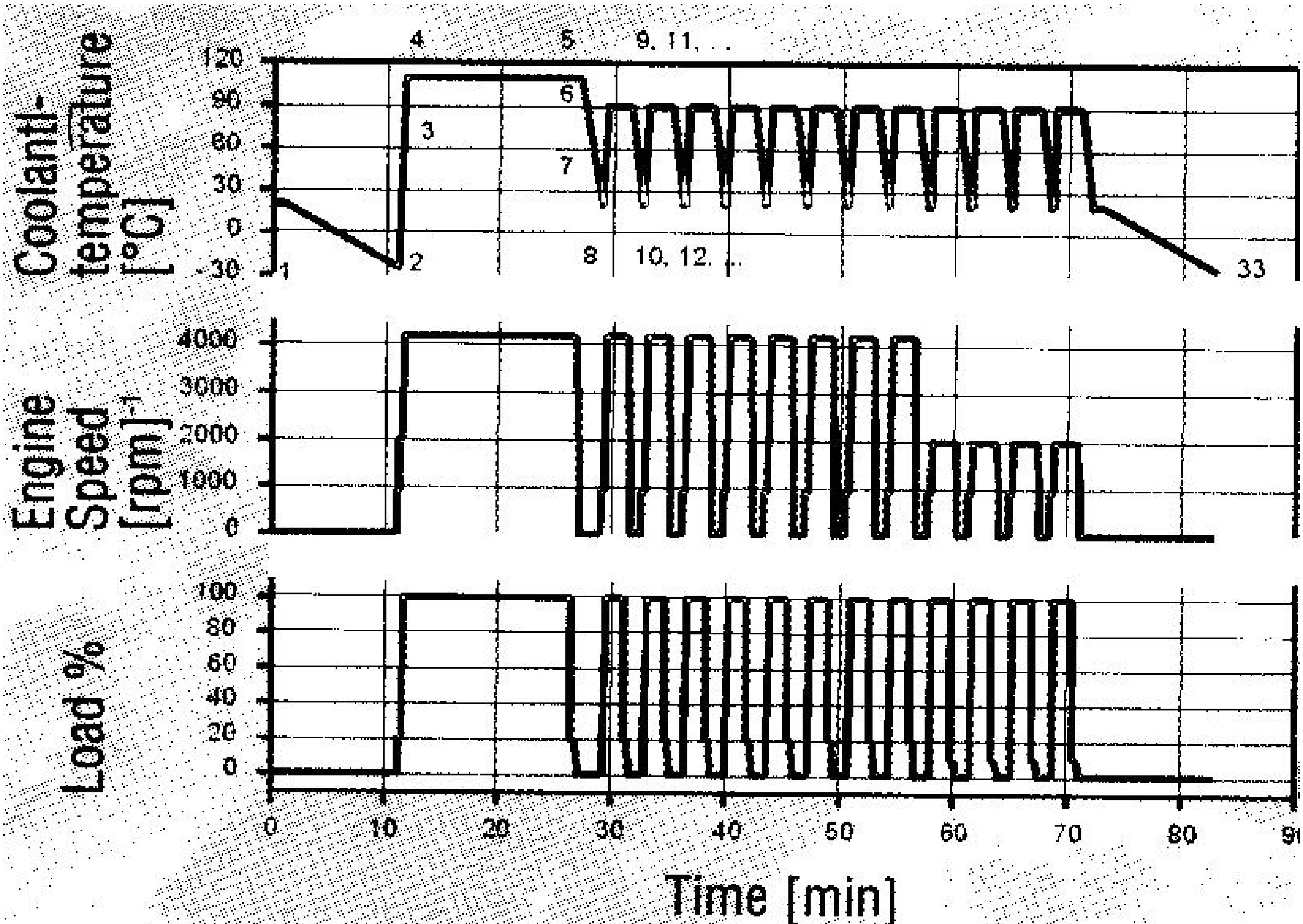
# Maximum Heat Input

- Normal rated speed and load
- Maximum component operating temperatures are attained and components whose durability life is largely controlled by the temperature of operation are assessed.
  - Piston( scuff, ring stick etc)
  - Valves and valve seats
  - Injector nozzle tip
  - Turbochargers and exhaust manifold

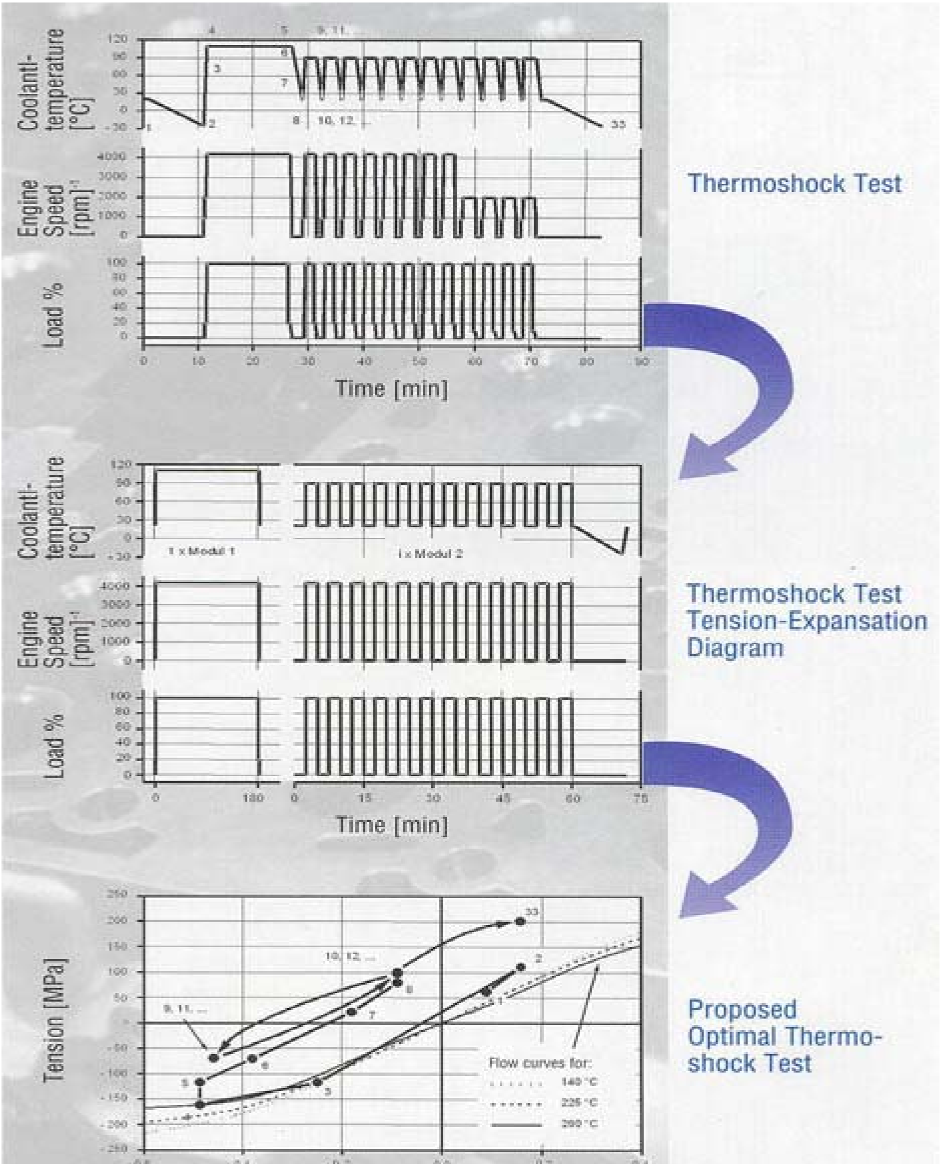
# Maximum cyclic temperature variation

- Thermal fatigue
- Found when the engine is operated between conditions of maximum and minimum heat input ( Running rated speed and load down to idle)
- Assess components whose durability is determined by the ability to withstand thermal fatigue
  - **Cylinder head assembly**
  - **Pistons**
  - **Manifolds, fixings**
  - **Turbocharger**

# Thermal shock test



# Thermal Shock Tests



# Maximum imposed mechanical load

- **Operating at maximum power and rated speed**
- With a turbo-charged diesel engine, this condition is normally encountered at maximum torque where the cylinder pressure is at a maximum and the lower operating speed leads to lower inertia relief.
- Components assessed include:
  - **Small end**
  - **Big end**
  - **Main bearings**
  - **Piston**
  - **Liner**
  - **Crankshaft**

# Maximum dynamic load

- **High inertia, maximum engine speed, low load. ( Diesel application governor run out )**
- Maximum stresses are applied to:
  - Valve train components
    - Camshaft
    - Cam followers
    - Valves
    - Springs

# Basic Validation Test Cycle

**Many manufactures increase the severity of their tests over what is found in normal service. Over speed, over fuelling etc.**

| | |
|---|---|
| ➢ Rated load and Speed | 20 min |
| ➢ No Load Governor run out | 10 min |
| ➢ Maximum Torque | 20 min |
| ➢ Idle | 10 min |

# Predictive Analysis a durability/validation test tool

**To be able to predict when a component will fail due to fatigue or wear out is a prerequisite to day.This can be achieved by:**

- Accelerated rig testing of key components
- Intelligent design validation testing with much attention paid to pre and post test strip, examination and measurement of critical components, regular lubricating oil analysis and exhaust gas particulate speciation are all valuable tools used in predictive analysis studies.

# Predictive Analysis ‘The How’ Typical example

- 1000 hour validation test. On the post test strip and measurement, it was noted that one cylinder bore has indications of wear and scuffing.
- It was noted that the particular cylinder top compression ring was worn
- Analysis of the oil samples taken at 50 hour intervals clearly showed a high level of chromium and Iron in the first 50 hour sample, there after no significant levels were noted.
- From this the engineer deduced that the cause was ingress of foreign matter in the top piston ring groove which was dislodged at some time within the first 50 hours of running.
- If however there had been chromium and iron in all 20 oil samples, then it would be possible to predict the projected life of the bore and indeed one would be able to alert the chief engineer to a possible coolant circulation problem leading to cylinder bore distortion.

# Validation duty cycles

- **To cater for the majority of cases and to ensure that components are assessed under the most severe operating conditions, it is usual to specify a test cycle that incorporates one the four extreme conditions we discussed earlier**

- The engine build and installation on the test bench should replicate that of the vehicle

# Automatic mapping

- **The trend toward automatic mapping  is a ongoing cause for concern.**
- **There are many and disparate variables to be considered, for example**
  - Fuel and ignition timing and duration
  - Variable valve timing
  - Variable Induction length
  - Variable EGR
  - Variable boost

# Automatic mapping

- **Changing many parameters simultaneously runs contrary to the engineers training , the mantra was change one thing at a time.**
- Times have changed, and we must use the available tools effectively
- In order to be able to identify major errors in Automatic mapping data, it is essential that the engineer has a deep understanding of the effect of individual parameter changes on all the associated outputs.
- Steady state loop studies in the running envelope are still required, and again when running the tests, **warning bells should ring if the results are too good**

# ENGINE TESTING

**GOLDEN RULES ~ Before a shaft turns !**

- **Know the precise build specification of the engine prior to start of test**
  - It will be impossible to replicate tests at some time in the future if one does have full records of build, cam timing, ignition timing, fuel and oil used, compression ratio.
- **The more detail you have, the better you sleep at night !**

# ENGINE TESTING

## GOLDEN RULES ~ Before a shaft turns!

- **Before starting the test, be clear why you have instigated the test**
- What do you hope to learn
- What are the key elements that you wish to glean from the test
- **Have you told the test technician what is required and why**

# ENGINE TESTING

## GOLDEN RULES ~ Before a shaft turns !

- **Write clear unambiguous test instructions**
- Discuss the test with the test technician
- Consider a basic pencil graph to be produced by the technician as the test progresses

# ENGINE TESTING

## GOLDEN RULES ~ Before a shaft turns !

- **Calibrate , Calibrate , Calibrate**
- Regardless of the objectives of the test, key items must be correct.
  - Indicated Load, Static and Dynamic
  - Engine Speed [rev/min]
  - Dynamometer input shaft speed [rev/min]

# ENGINE TESTING

## GOLDEN RULES ~ The real World !!

- **Suspect all results**
- The better the apparent data the greater the need for suspicion
- Straight line trend curves do not happen in real life

# ENGINE TESTING

- **TAKING READINGS**
- Allow engine to stabilise at each set point
- Oil and coolant temperatures  to be held constant to pre-determined limits
- Allow a minimum of 5 minutes between each set of readings
- Instigate fuel and emission readings at the end of the stabilisation period

# ENGINE TESTING

- **Repeatability of tests**
- In order to be able to repeat test results, in addition to knowing the build of the engine, it is necessary to correct the results back to a standard induction temperature and barometric pressure within the test cell
- There are various standards for N/A and turbo, diesel and gasoline applications

# ENGINE TESTING

## CALLIBRATION

- Instruments and test equipment must be calibrated at test facility specified calibration intervals and must have current laboratory calibration records.

- Full tractability of all calibration records is a prerequisite of all professional engine test laboratories

# ENGINE TESTING

- **NEED TO REPEAT ALL PERFORMANCE TESTS**
- In order to have statistical confidence in the results of any performance test, it is necessary to the repeat the test at least twice, if possible three times.

**Another *GOLDEN RULE***

**DO IT ONCE**

**DO IT CORRECTLY EACH TIME, EVERY TIME**

# TESTING GOLDEN RULES

- **SUSPECT ALL RESULTS**
- **CHECK AND CROSS CHECK CALIBRATION**
- **ENSURE THAT YOU HAVE CLEAR UNAMBIGUOUS INSTRUCTIONS**
- **RECORD ALL RESULTS THE GOOD AND THE BAD**

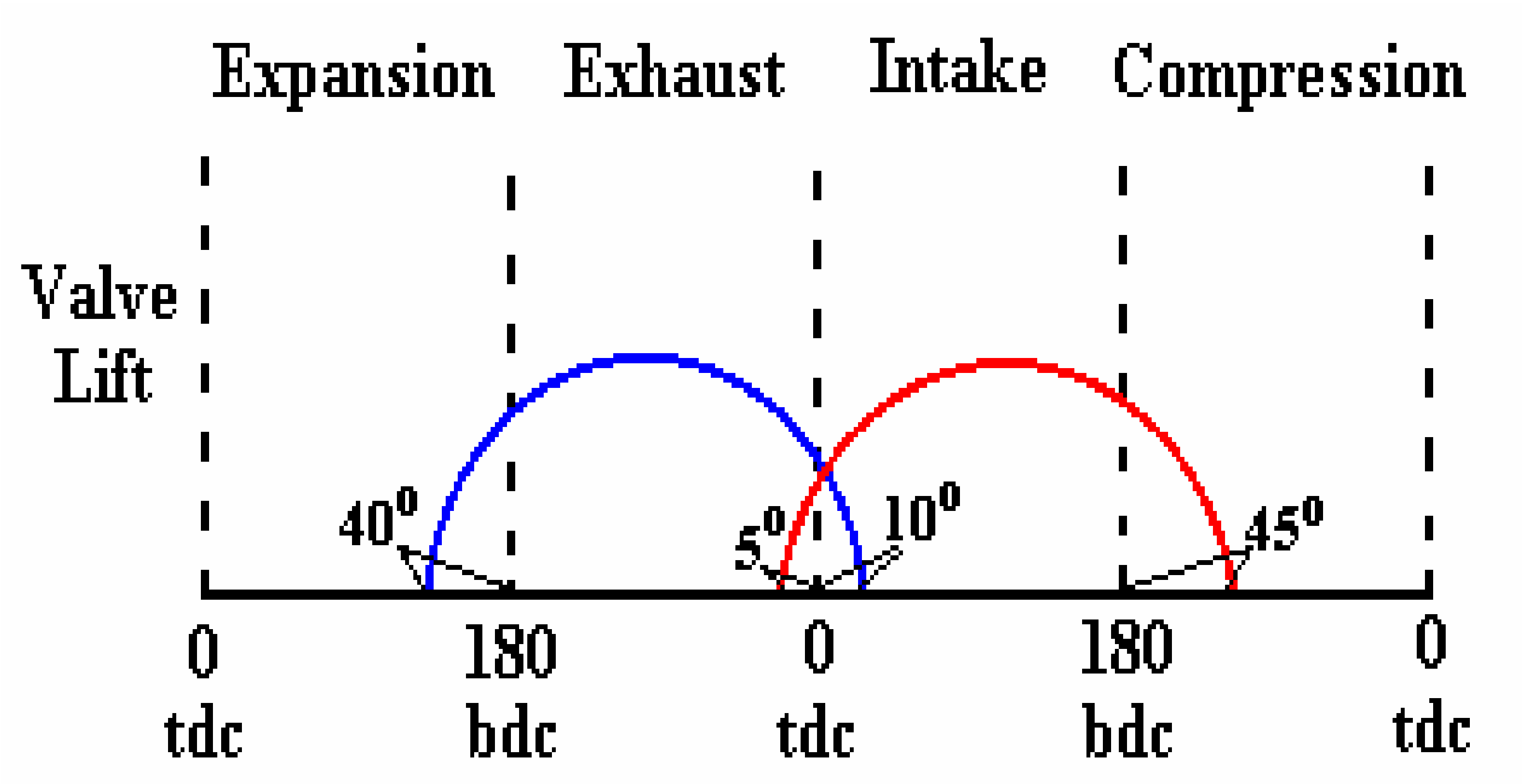
# What does performance testing give the engineer

- A means of comparing differing engine build specifications , one with another

- An aid to engine development from design level one to production sign off

- A production quality tool

# Preferred method of showing valve timing



# MAXIMUM POWER ~ PERFORMANCE TEST

\# Always complete a rough hand drafted graph of the results.

\# Is the fuel delivery a straight line ?

\# Do the SFC and Torque mirror each other

\# Build up your own memory joggers

# PERFORMANCE TESTING

Build up your own memory joggers

**NOT POSSIBLE RE-TEST !!**

**TREAT THESE RESULTS WITH CAUTION**

**OK**

**THE RESULTS ARE BELIEVABLE**

**TREAT THESE RESULTS WITH CAUTION**

# PERFORMANCE TESTING


**WHAT IS WRONG WITH THIS !!!!**

# PERFORMANCE TESTING

- Repeatability of tests
- In order to be able to repeat test results, in addition to knowing the build of the engine, it is necessary to correct the results back to a standard induction temperature and barometric pressure within the test cell
- There are various standards for N/A and turbo, diesel and gasoline applications

# PERFORMANCE TESTING

- **Correction to 88/195/EEC**
- Spark ignition
- Correction factor $cf = \left[\frac{99}{p_s}\right]^{1.2} \times \left[\frac{T}{298}\right]^{0.6}$

Where T=the absolute intake temp in Kelvins

$p_s$=dry atmospheric pressure in kilopascals kPa less the water vapour pressure

**N.B. for the test to be valid, the correction factor must lay between 0.93 and 1.07**

# PERFORMANCE TESTING

- **Correction to 88/195/EEC**
- Diesel Compression ignition N/A

- Correction factor $cf = \left[\frac{99}{p_s}\right] \left[\frac{T}{298}\right]^{0.7}$

Diesel Compression ignition Turbo

- Correction factor $cf = \left[\frac{99}{p_s}\right]^{0.7} \times \left[\frac{T}{298}\right]^{1.5}$

# PERFORMANCE TESTING

- Some base calculations
- Swept volume [displacement]of a cylinder
- 4 stroke $V_h = \frac{\tilde{n} * d^2 * s}{4}$ # d = bore in mm

  # s = stroke in mm
- 2 stroke $V_f = \frac{\tilde{n} * d^2 * s}{4}$
- Swept volume of engine $V_H = V_h * z$

  # z = number of cylinders

# PERFORMANCE TESTING

- Compression
- Compression ratio
- $CR = \frac{V_h + V_c}{V_c}$ $V_c$ = Cyl. comp. volume
  $V_h$ = Swept vol. of cylinder

# PERFORMANCE TESTING

- **Gasoline applications ~ Ignition timing**
- Determination of ignition timing at differing speed and load conditions
- The test is conducted throughout a wide range of ignition advance positions in order to determine engine performance levels with differing load conditions

# PERFORMANCE TESTING

- **Gasoline applications**
- Determination of ignition timing
- The test is conducted throughout a wide range of ignition advance positions in order to determine engine performance levels with full load advance
- Fuel is set to L B T /M B T at the required test speed

# PERFORMANCE TESTING

- **Determination of part load ignition timing**
- These tests are conducted to establish the points of minimum specific fuel consumption relative to optimum spark advance.
- By running a series of loops throughout the speed range, and maintaining specified BMEP figures, a final part load ignition curve can be established

# PERFORMANCE TESTING

- **Determination of ignition timing ~ part load procedure :**
- Set throttle position as required/select dynamometer constant speed mode.
- Establish MBT at required speed/load
- Start loop, retard ignition by 14° /reset load with throttle
- Allow conditions to stabilise

# PERFORMANCE TESTING

## Determination of ignition timing ~ part load procedure

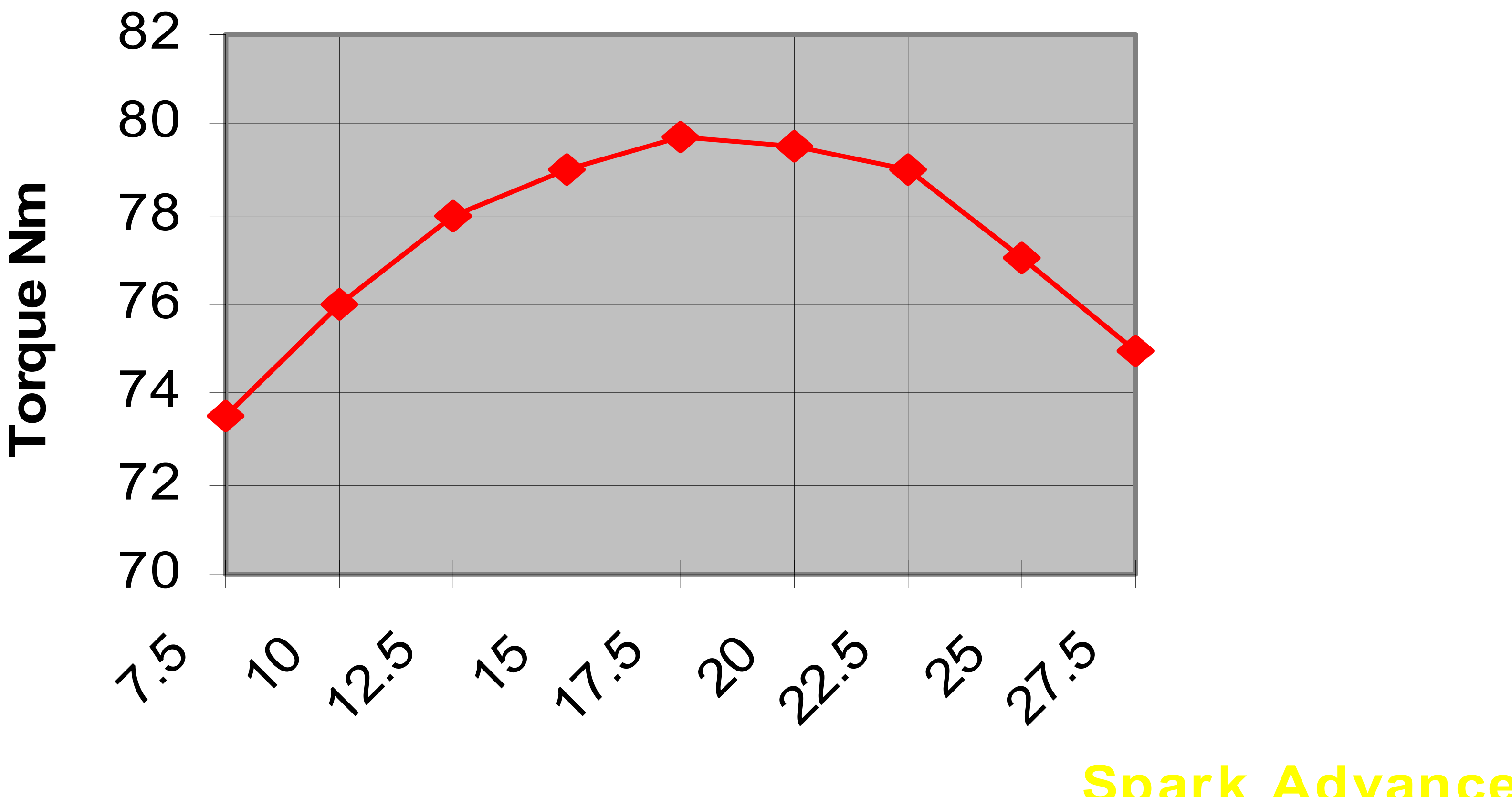
- Set throttle position as required/select dynamometer constant speed mode.
- Establish MBT at required speed/load
- Start loop, retard ignition by 14° /reset load with throttle
- Allow conditions to stabilise

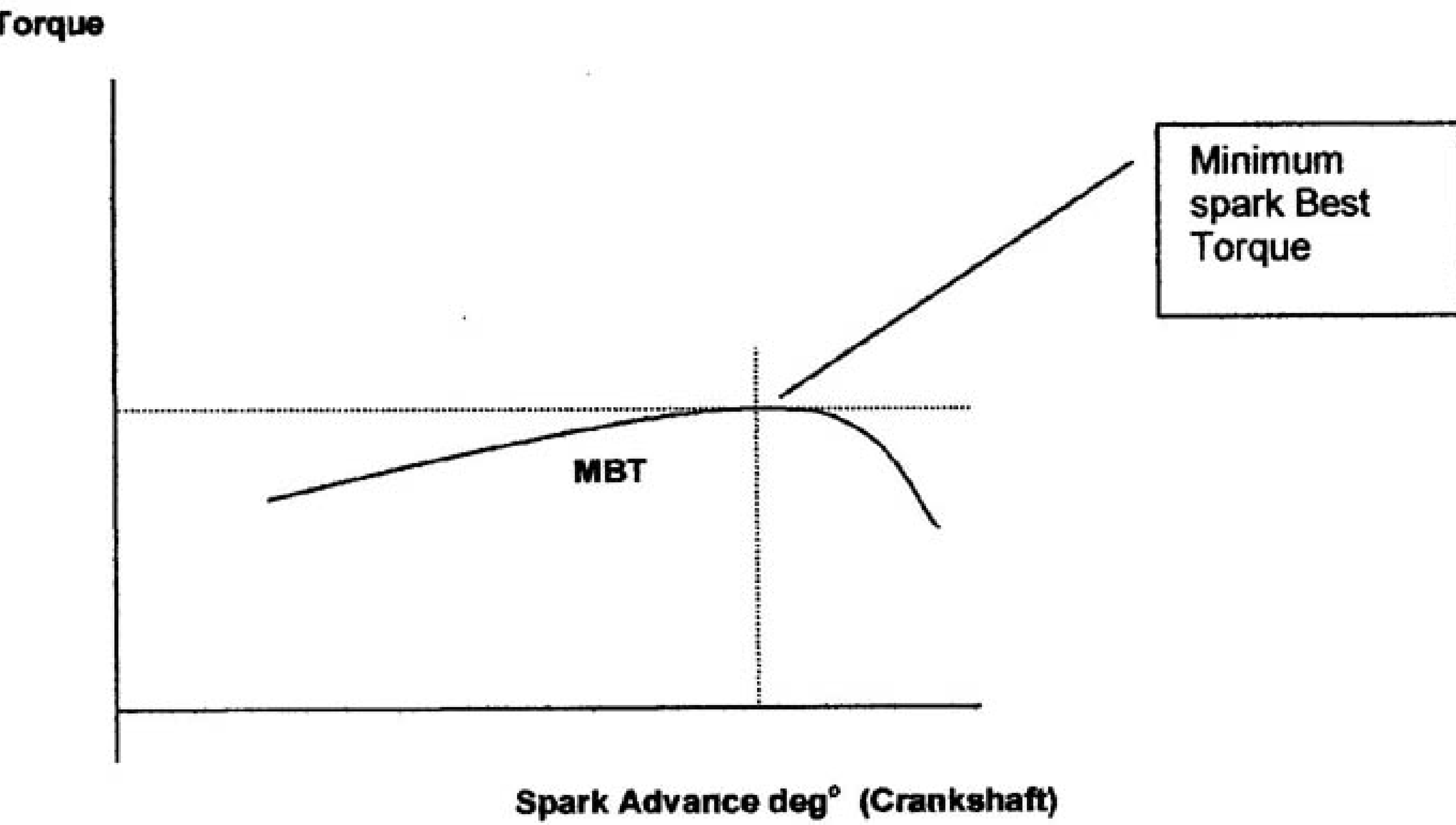
# PERFORMANCE TESTING

- **Determination of ignition timing ~ part load procedure :**
- Take all readings after stabilisation
- Advance ignition by 2 ° , continue the loop until ignition is 10° adv from MBT
- Do not advance into heavy detonation
- When starting do retard beyond TDC

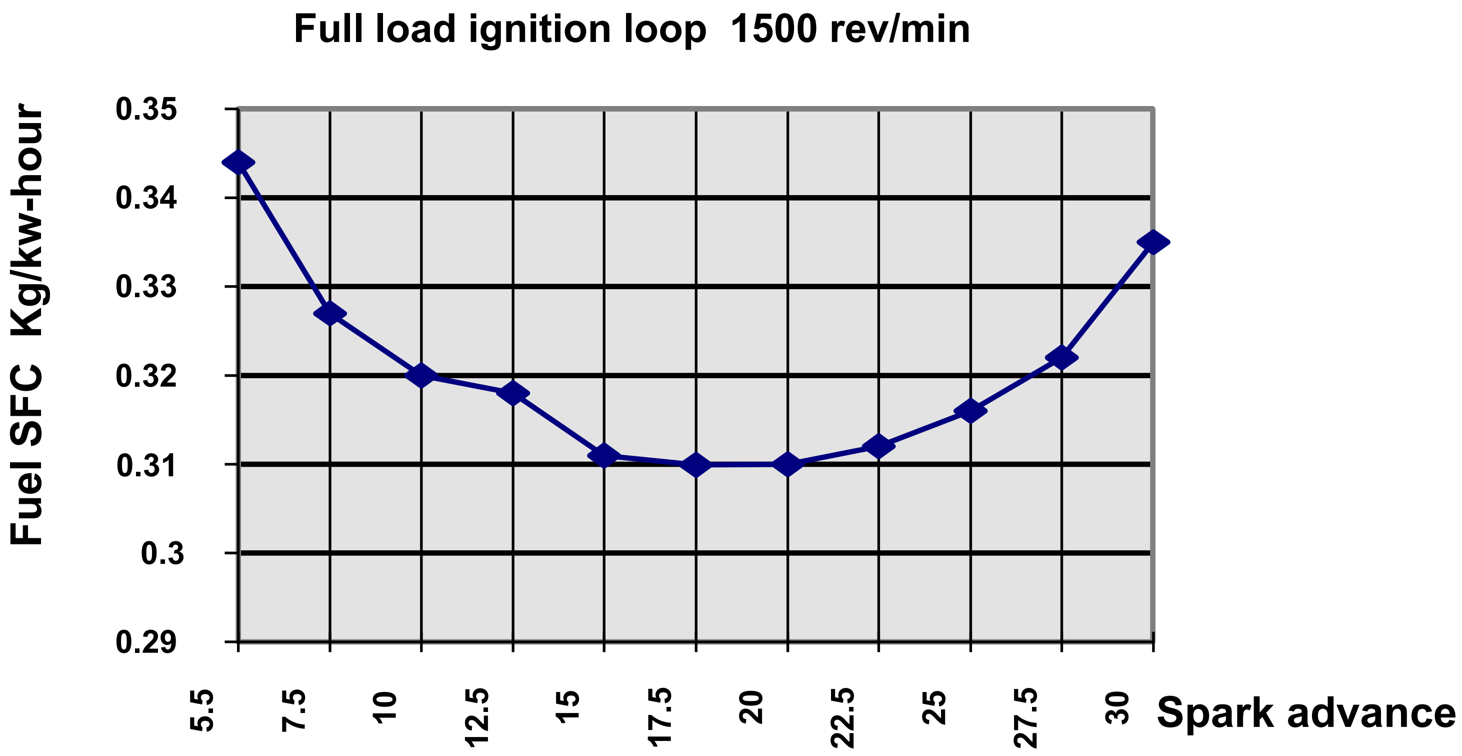
# PERFORMANCE TESTING

## Full load 1500 rev/min ignition loop

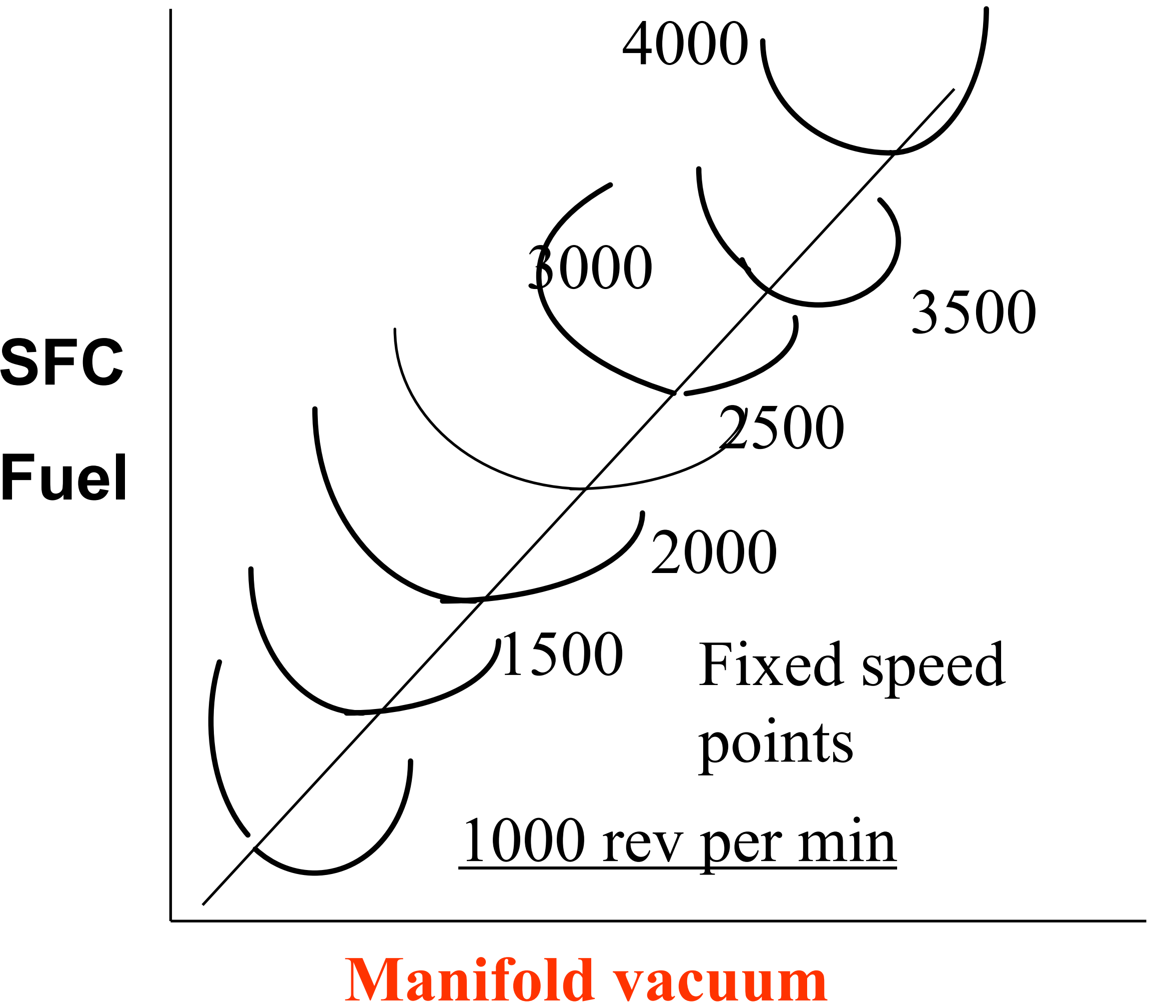



Torque
Minimum spark Best Torque
MBT
Spark Advance deg° (Crankshaft)

# PERFORMANCE TESTING



# PERFORMANCE TESTING




**Fuel loops constant throttle setting**

Note: The minimum fuel maximum torque point at each fixed speed, gives a near straight line curve for any given throttle setting

# Effect of spark change

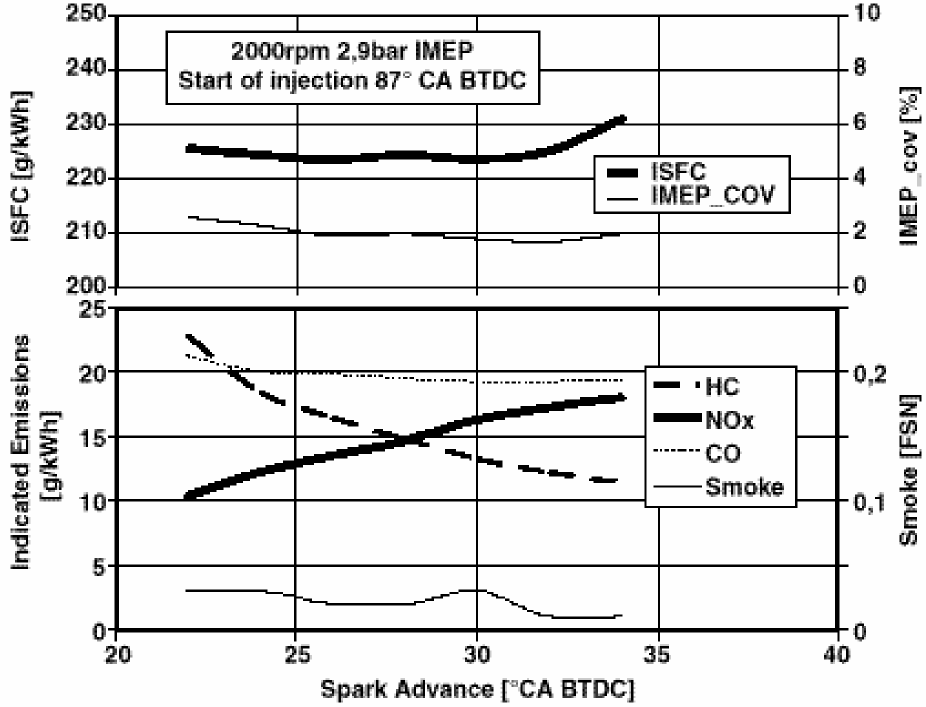



Fig. 6: Spark timing variation.

# PERFORMANCE TESTING

## Engine Instrumentation

- Air cleaner differential pressure
- Boost ( if applicable) centre of inlet manifold
- EGR Vacuum/pressure
- EBP 75mm+/-10mm down stream of mating flange
- Fuel supply pressure, +ve.. : -ve..
- Intake manifold vacuum centre of manifold
- Oil Pressure ; Engine gallery take off position
- Temperature Thermocouples always as close to outlet/inlet as possible in a position where flow is unrestricted
- Fuel temperature, measure as close to the measuring head as possible

# PERFORMANCE TESTING

## CALIBRATION

Instruments and test equipment must be calibrated at test facility specified calibration intervals and must have current laboratory calibration records.

Full tractability of all calibration records is a prerequisite of all professional engine test laboratories

# PERFORMANCE TESTING

## PRESENTATION OF DATA

Data to be plotted against engine speed

- Corrected B.M.E.P. - kPa ( psi)
- Corrected Torque - Nm ( lb-ft)
- Corrected Power - kW ( BHP)
- Fuel Flow - kg/hr ( Lb/hr)
- SFC - g/kW-hr ( Lb/HP-hr)
- Spark Advance/Injection point ° crankshaft
- Intake manifold vacuum - kPa ( in. Hg)
- Exhaust back pressure - kPa (in.Hg)
- CO% (etc) at exhaust manifold flange

# PERFORMANCE TESTING

## Engine Instrumentation

- **<u>ACCURACY</u>**
- Fuel flow +/-1% of reading
- Pressure +/- 0.5% of full scale
- Speed +/- 5 rev/min throughout range
- Injection/spark +/- 0.5° of reading
- Temperature +/- 1.5 ° C up to 150° C
- Temperature +/- 3.5° C between 150° and 1000°
- Torque +/- 0.5Nm or +/-1% of full scale
- Emissions +/- 3% of full scale

# PERFORMANCE TESTING

- **TAKING READINGS**
- Allow engine to stabilise at each set point
- Oil and coolant temperatures to be held constant to pre-determined limits
- Allow a minimum of 5 minutes between each set of readings
- Instigate fuel and emission readings at the end of the stabilisation period

# PERFORMANCE TESTING

- **NEED TO REPEAT ALL PERFORMANCE TESTS**
- In order to have statistical confidence in the results of any performance test, it is necessary to the repeat the test at least twice, if possible three times.

# PERFORMANCE TESTING

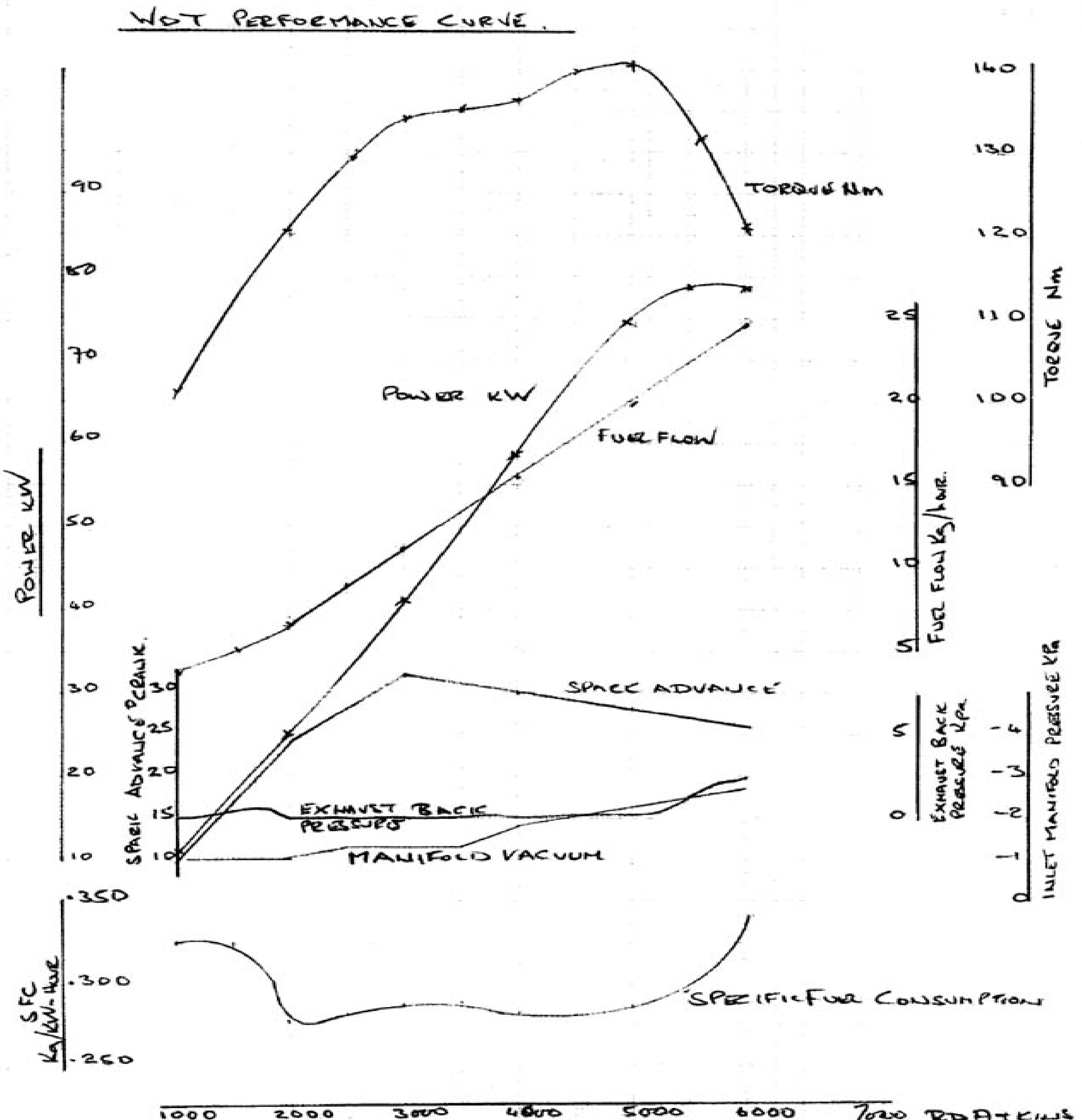
- **MAXIMUM POWER ~ PERFORMANCE TEST~ WOT PC**

  # Always complete a rough hand drafted graph of the results.

  # Is the fuel delivery a straight line ?

  # Do the SFC and Torque curves mirror each other

  # Build up your own key rules for further reference




**Wide**

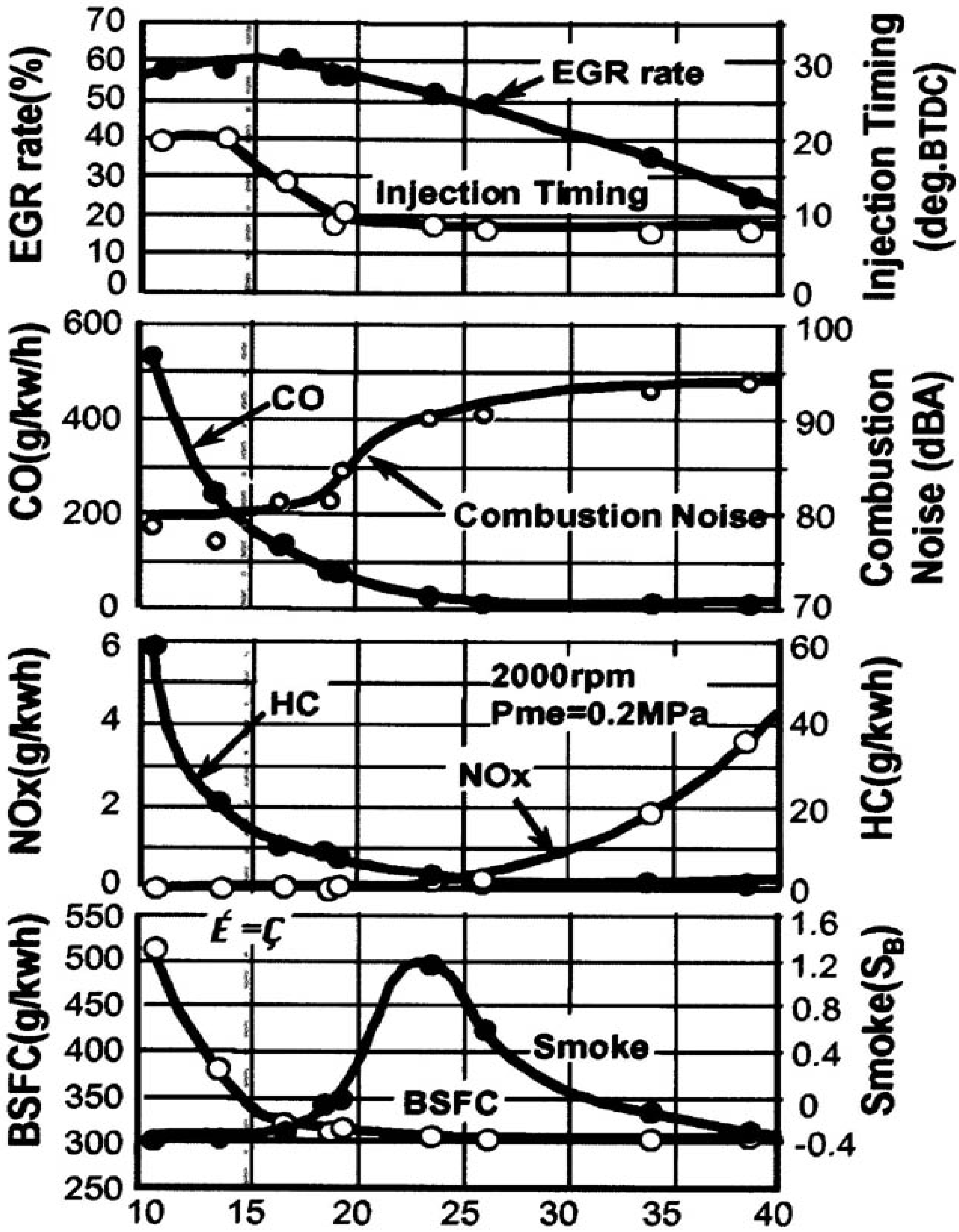
**Open**

**Throttle**

**Power**

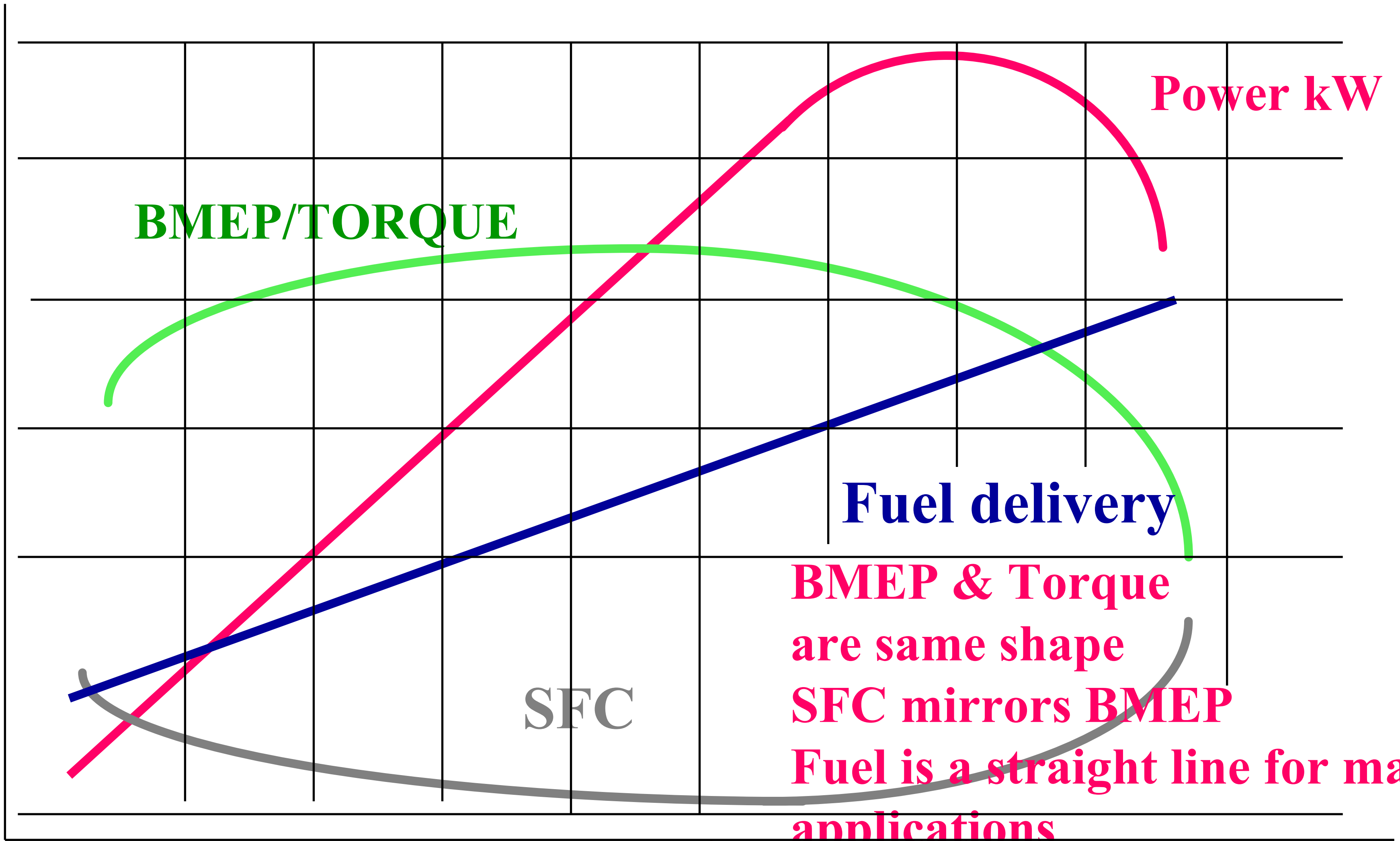
**Curve**

**WOT.PC**




# Changes to AFR and the effect on EGR; CO; N0x; BSFC

# TYPICAL POWER CURVE




BMEP & Torque are same shape
SFC mirrors BMEP
Fuel is a straight line for man
applications

# Effects of air/fuel ratio/Gasoline engines

- Air fuel ratio; mass of air in charge to mass of fuel
- Stoichiometric ratio;the ratio where there is exactly sufficient O2 present for complete combustion ; Ranges 14: to 15:1~ 14.7:1 is the accepted norm.
- Lambda excess air factor, the ratio of actual to stoichiometric air/fuel ratio. The range is from 0.6 (rich) to 1.5(weak)
- Lambda ratio has a great influence on power, fuel consumption and emissions.

# PERFORMANCE TESTING

- **Testing terminology**
- LBT Leanest fuel for best torque
- MBT Minimum spark for best torque
- MBT-L MBT Retarded to clear detonation
- TLA Top limit advance
- BLA Bottom limit advance
- OCT Oil consumption test
- Carbon Hours Engine running hours since last de-carborisation

# PERFORMANCE TESTING

## Measurement of mechanical losses

- Indicator diagram
- Motoring tests
- Morse tests
- Willans line
  - We will consider the last three

# Morse Test

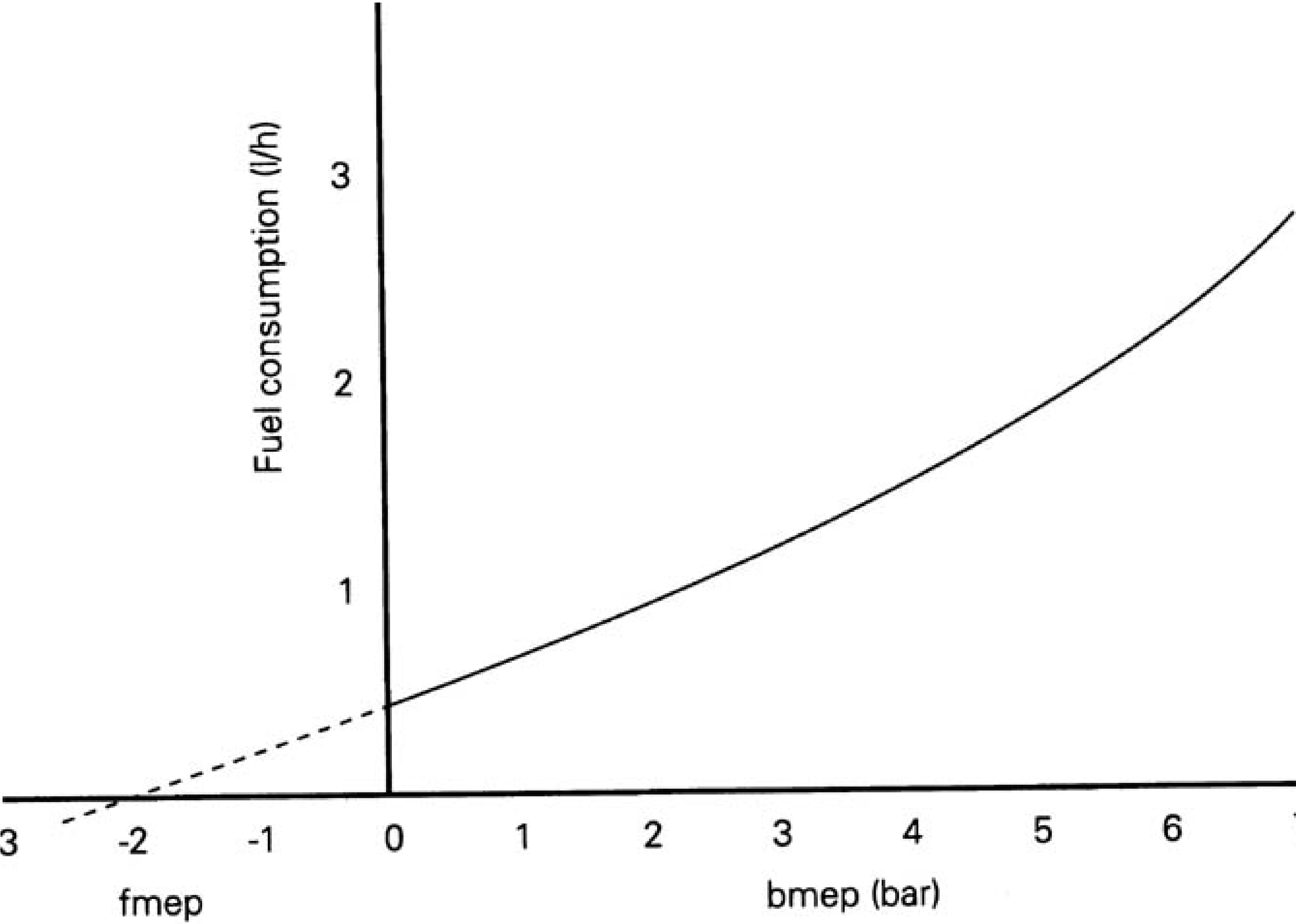
| | | MECHANICAL EFFICIENCY BY MORSE TEST | | | | | | |
|---|---|---|---|---|---|---|---|---|
| EV/MIN | TOTAL IND POWER kW | Cyl No 1 kW | Cyl No 2 kW | Cyl No 3 kW | Cyl No 4 kW | Brake powe kW | Friction Powe kW | Mechanic efficiency |
| 1000 | 9.08 | 2.29 | 2.25 | 2.27 | 2.28 | 7.86 | 1.22 | 86 |
| 1500 | 16.15 | 3.86 | 4.19 | 4.27 | 3.82 | 13.32 | 2.83 | 82 |
| 2000 | 22.83 | 5.72 | 5.68 | 5.76 | 5.68 | 19.02 | 3.81 | 83 |
| 2500 | 28.12 | 7.12 | 6.91 | 6.99 | 7.09 | 24.50 | 3.61 | 87 |
| 3000 | 36.00 | 9.13 | 8.91 | 8.97 | 9.00 | 29.95 | 6.05 | 83 |
| 3500 | 42.40 | 10.77 | 10.48 | 10.52 | 10.63 | 35.18 | 7.22 | 82 |
| 4000 | 50.68 | 12.88 | 12.50 | 12.71 | 12.59 | 40.73 | 9.95 | 80 |
| 4500 | 58.05 | 14.70 | 14.37 | 14.56 | 14.42 | 44.43 | 13.62 | 76 |
| 5000 | 63.56 | 16.34 | 15.76 | 16.02 | 15.45 | 46.70 | 16.86 | 73 |
| 5500 | 69.74 | 18.00 | 17.25 | 17.42 | 17.08 | 48.98 | 20.76 | 70 |
| 6000 | 75.83 | 19.54 | 18.66 | 18.91 | 18.72 | 50.14 | 25.70 | 66 |
| | | | The average mechanical efficiency is 79.31% | | | | | |

# PERFORMANCE TESTING

## The WILLAN'S Line Method

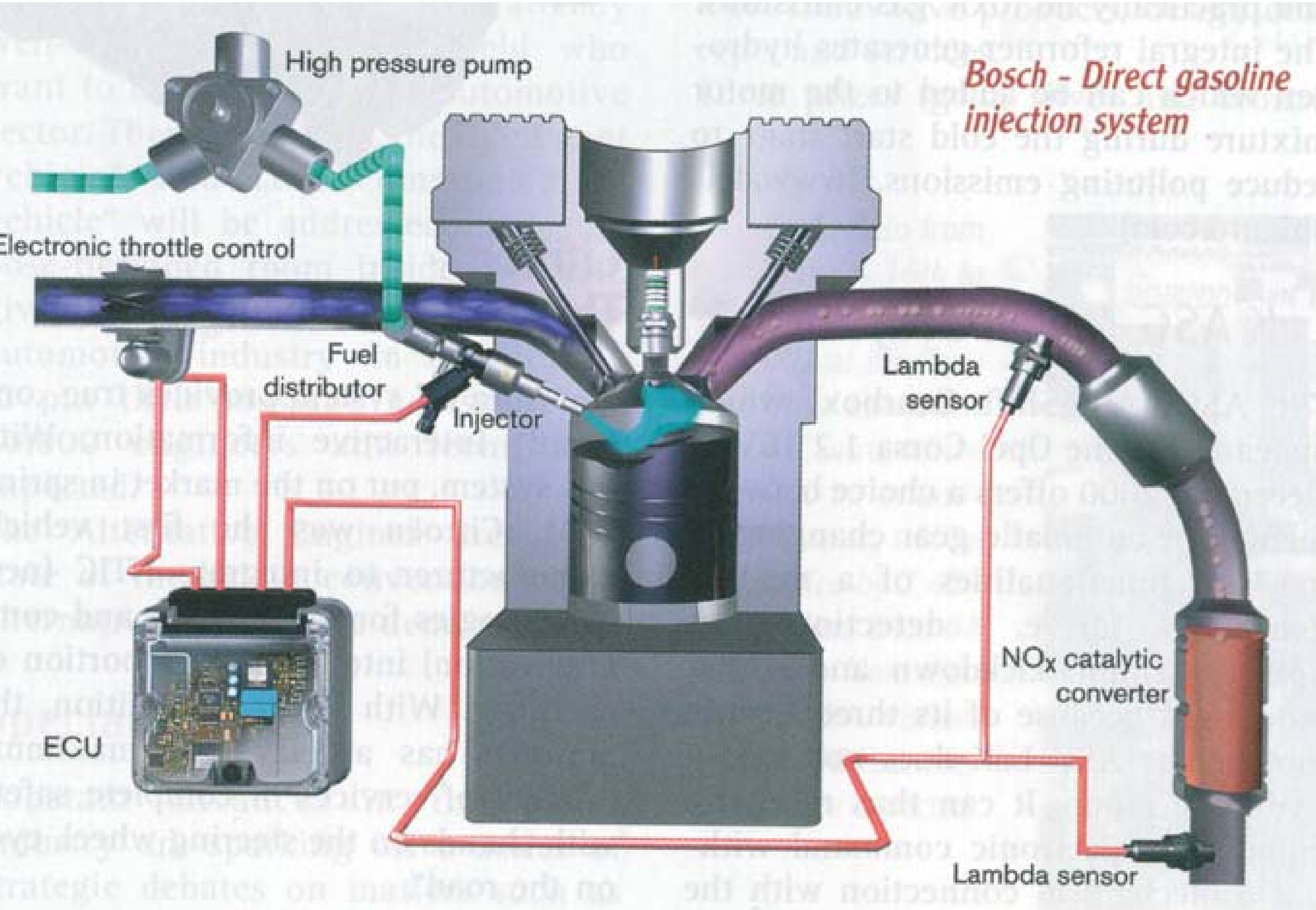
Applicable mainly for diesel engines

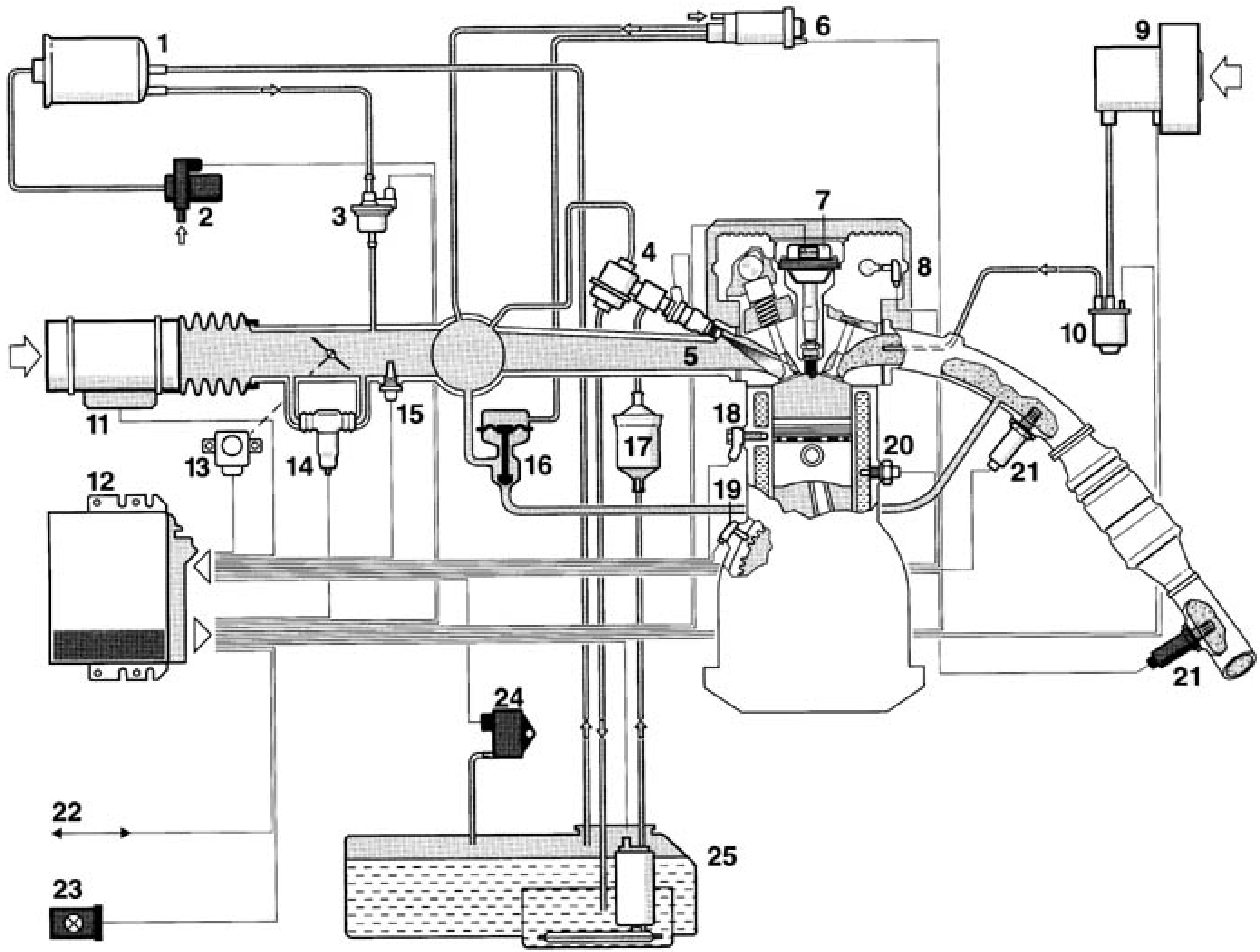
- The curve of fuel consumption rate against torque at constant speeds plots well as a straight line up to 75% of full power.
- Equal increases in fuel give equal increases in power ( combustion efficiency being constant)
- At zero power, all fuel burned is expended in overcoming mechanical losses.
- Extrapolation of the Willan's line to zero fuel consumption gives a measure of friction losses in the engine


Fuel consumption (l/h)
3
2
1
3
-2
-1
0
1
2
3
4
5
6
7
fmep
bmep (bar)

# Major causes of mechanical failure

- Rubbing or sliding movement
- Vibration induced by the firing strokes of the engine
- Out of balance reciprocating masses


Bosch - Direct gasoline injection system
High pressure pump
Electronic throttle control
Fuel distributor
Injector
Lambda sensor
ECU
NOx catalytic converter
Lambda sensor



1
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# PERFORMANCE TESTING

## Diesel - Cetane Number

Cetane number is the most important diesel fuel specification. It is an indication of the extent of ignition delay.

The higher the cetane number the shorter the ignition delay, the smoother the combustion and the cleaner the exhaust

Cold starting is easier the higher the cetane number

# PERFORMANCE TESTING

## Calorific value

- The calorific value of diesel fuel is lower than that of gasoline.
- Diesel fuel ranges from 40MJ/kg to 43MJ/kg and is a function of fuel density
- The higher the sulphur content the lower the calorific value, this has a big impact upon new emission regulations

**UNDERSTANDING DESIGN VALIDATION TESTING**

- **A SIGNIFICANT WEAPON IN THE AUTOMOTIVE ENGINEERS ARMOURY**

# Design ValidationTesting

- **All tests must be thought through**
- Laboratory experiment
- Relevance of the test
- test practices
- Accuracy of results
- Confidence in the test
- Cost effectiveness

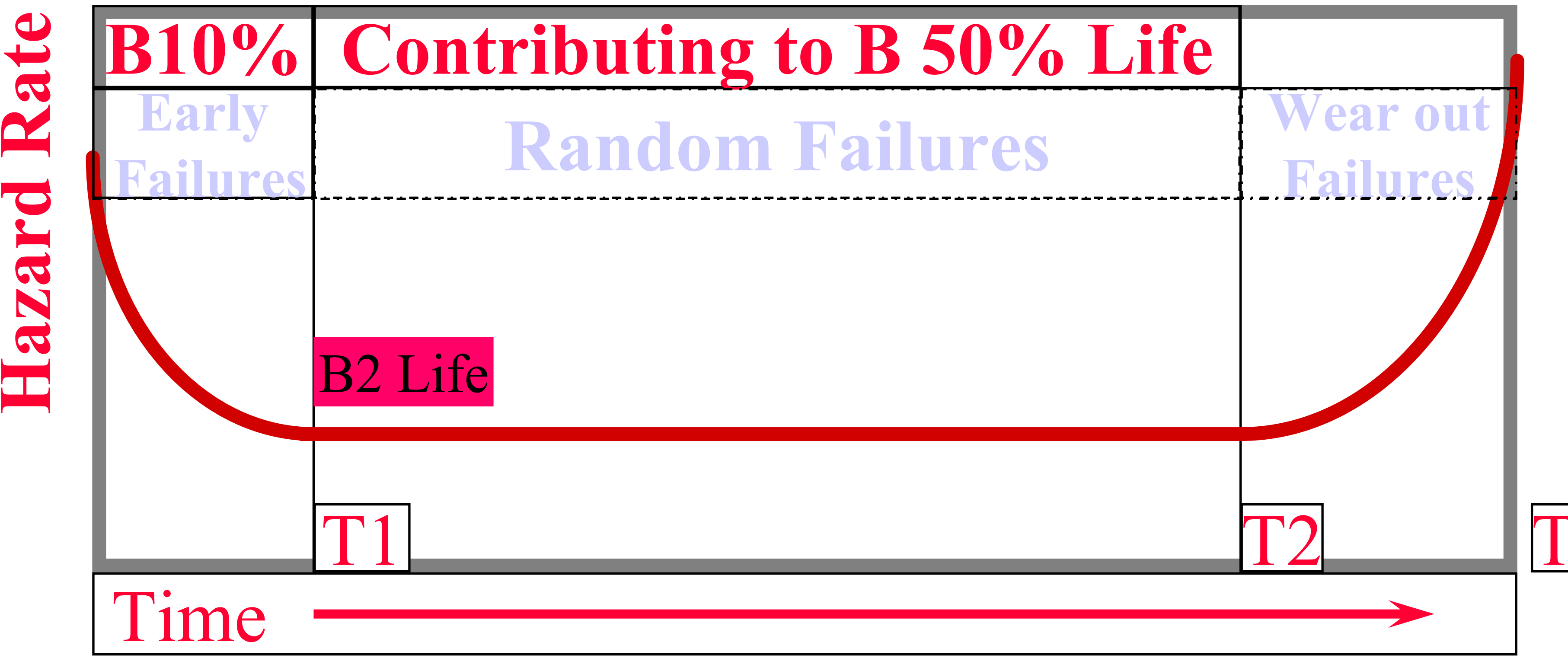
# Why undertake Design Validation Testing

- It is essential to know prior to starting production that a item or assembly is capable of lasting and resisting accelerated wear within its designed life
- Computer modelling is only part of the answer
- This paper out lines the means of determining the type of test and number of tests required to meet the engines original design objectives

# ENGINE LIFE

- No clear cut engineering definition of engine life exists
- General definition of engine life is the time when key components have to be replaced and the engines performance no longer lies within legislated limits
- Industry definition values for engine life are defined in terms of B10% and B50% this being the time when 10% or 50% of the items under test have failed

# Hazard Failure Rate as a Function of Time'Bath Tub Curve !!!!'



# Relating failure rate to engine life

- **In Design levels one and two, initial failure rate reduces to a point where it remains near constant**
- This is referred to as the **B2 life**
- Failures are random in nature due to :
- Design
- Material specification
- Production

# Major causes of mechanical failure

- Rubbing or sliding movement
- Vibration induced by the firing strokes of the engine
- Out of balance reciprocating masses

# Confidence in Reliability

- From the confidence level formulae, it will be seen that to have a reliability of 90% with a confidence level of 90% a total of 22 tests are required

- For the same reliability, one test gives a confidence level of 10% whilst two tests increase this to 19%

- Statistical determination of reliability cannot be made from 1 or 2 tests with any degree of confidence.

# Confidence Level

- Statistical analysis states that for a test series carried out without failure for the specified life the confidence level can be calculated as follows:-

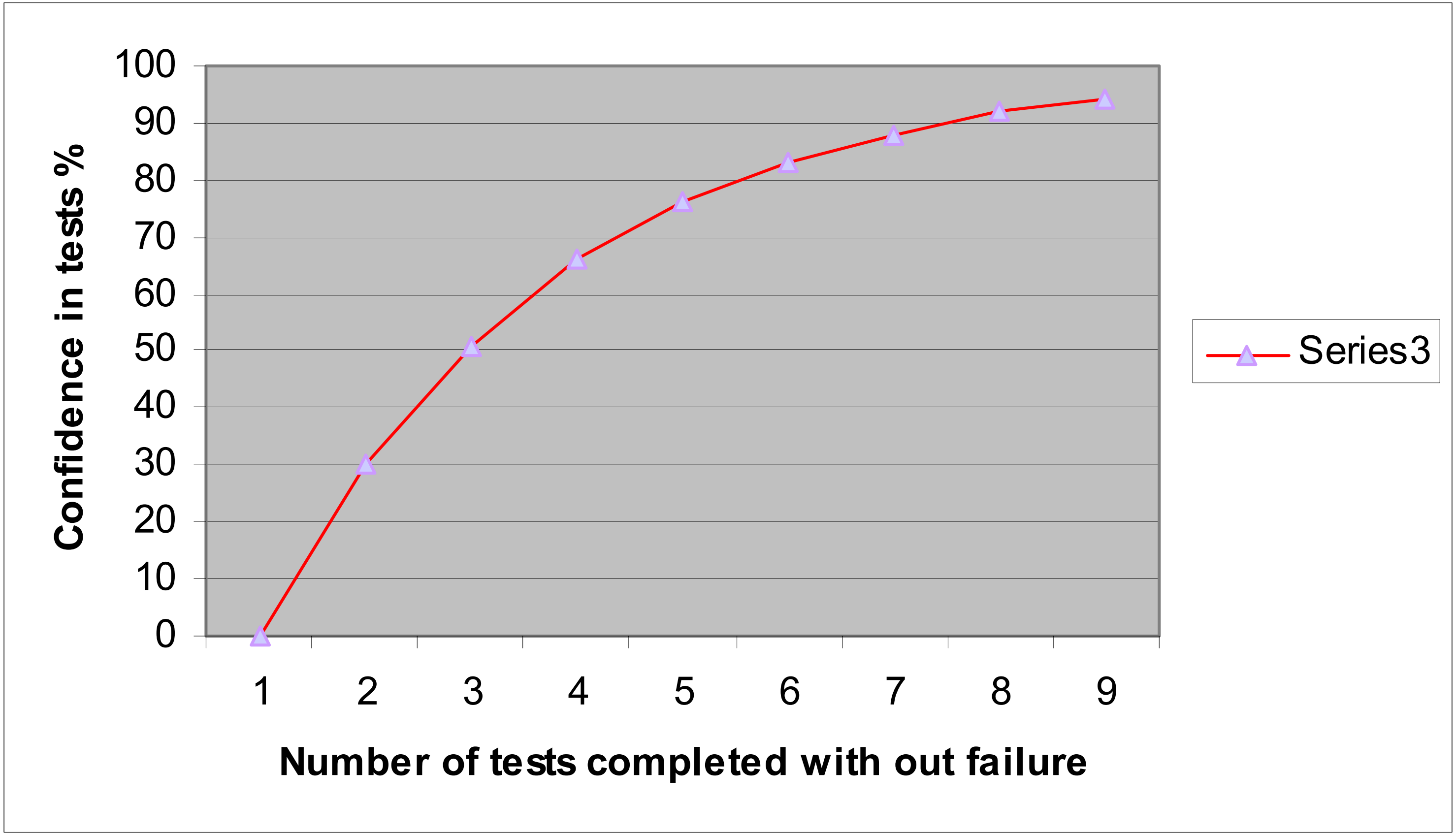
$$CL = 1 - R^n$$

CL = Confidence level

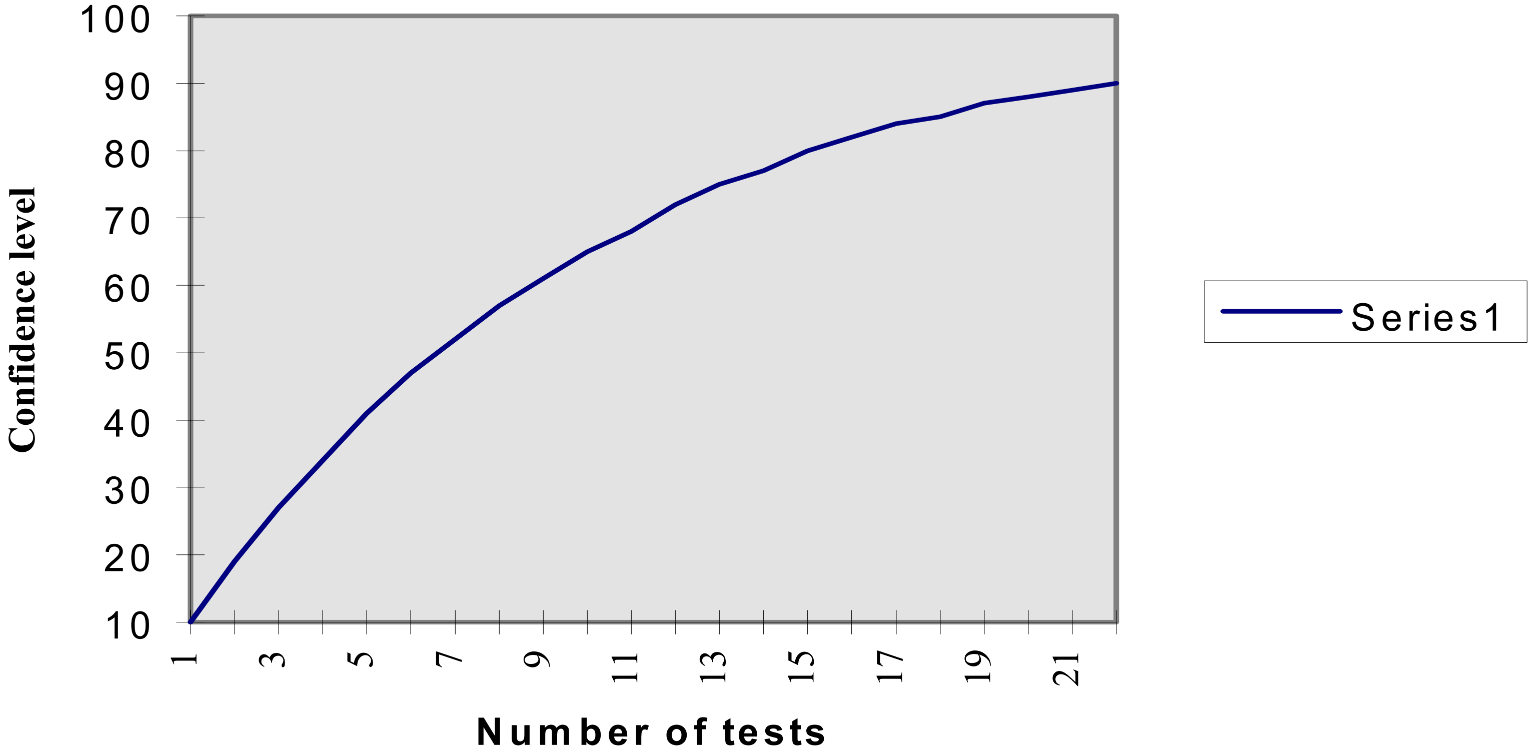
R = Reliability

n = Number of tests completed with out failure

# With a reliability of 70%, note the number of tests to give confidence is much reduced



# Confidence level percentages when running with a mean reliability of 90%
# A plot of confidence level % against No of tests



# Engine Application

- Objective is to establish the probability of a given product reaching its design life which in turn may be dictated by legislation
- Bench tests must replicate and accelerate in service life conditions
- A typical representative test cycle for all engine applications is not possible
- Specialist tests have been developed to test engines over the 4 most important operating conditions

# Major causes of mechanical failure

- Rubbing or sliding movement
- Vibration induced by the firing strokes of the engine
- Out of balance reciprocating masses

# The four most important mechanical test conditions

- **Maximum Heat input.**
  **Rated Speed and Load**
- **Thermal Fatigue.**
  **Maximum Cyclic Temperature Variation**
- **Mechanical Load**
  **Maximum Imposed Mechanical Load**
- **Dynamic Load**
  **Maximum engine speed. no load**

# Maximum Heat Input

- Under these conditions , maximum component operating temperatures are attained and components whose durability is largely controlled by the thermal gradient of operation are assessed

- These components include:
  Piston ( scuff/ring stick etc)
  Valves and valve seats
  Injector nozzle
  Turbocharger

# Maximum Cyclic Temperature Variation

- These conditions occur when the engine is alternately operated between conditions of maximum and minimum heat input

- To test and assess internal and external components whose durability is determined by their ability to withstand thermal fatigue.

- Components include

  Cylinder head (Valve bridge area)

  Cylinder head gasket and fixing bolts

  Piston,exhaust,turbo charger and fixings

# Maximum Imposed Mechanical Load

- With a turbo charged engine this condition is normally encountered at maximum torque where cylinder pressure is at a maximum and the lower operating speed reduces the extent of inertia relief.

- Components assessed include
  Small end, big end and main bearings
  Piston
  Liner and crankshaft

# Maximum Dynamic Load

- This high inertia condition occurs at the maximum engine speed, normally governor run out speed at no load.

- Maximum stresses are applied to
  Valve train components
  Piston small end
  Main and big end bearings

# Tests in the development of prototype engines

- Manufactures utilise variation of these four test types, testing under severe loading conditions
- Tests of 100 to 200 hours are sufficient to screen new designs ( see ‘Bath Tub Curve’)
- These tests provide sufficient confidence to consider longer term extended engine approval tests

# Durability Duty Cycles

- To cater for the majority of cases and to ensure that components are assessed under the most severe operating conditions, it is usual to specify a test cycle that incorporates one the four extreme conditions we discussed earlier

- The engine build and installation on the test bench should replicate that of the vehicle

# Basic Durability Test Cycle

| | |
|---|---|
| • **Rated load and Speed** | **20 min** |
| • **No Load Governor run out** | **10 min** |
| • **Maximum Torque** | **20 min** |
| • **Idle** | **10 min** |

Many manufactures increase the severity of their tests over what is found in normal service. Over speed, over fuelling etc.

# Why increase the severity

- Increasing the severity of tests is of value by reducing the time to complete the tests and thus increasing the confidence level in the analysis of the results

- Early in a new engine programme at least two durability tests  of 1000 hours duration should be undertaken

# Caution !!!

- The specification of severe tests requires extreme care and can only normally be achieved by reference to historical data.
- Any one can specify tests of extreme severity which lead to early failure, these cannot be related to normal service and are of dubious worth
- Development on this basis results in the engine being over designed and non competitive

# Design Validation Tests

- Each engine type and application could have its own suit of tests, but we will discuss a few of the more common types of test that used within the industry.
- The objective of this work, is to demonstrate that no major deficiencies are present in the design of the engine

# Duration of Durability tests

- **Four aspects to be considered**

1. Verification that wear will not prevent the expected designed service being achieved

2. Verification that failure due to mechanical fatigue will not occur

3. Verification that failure due to thermal fatigue will not occur

4. Emission and legislative performance to be maintained within the warranty life of the vehicle

# Life of engineering materials

- The endurance limit for typical engineering materials used in engines is quoted as being between $10^6$ and $10^7$ cycles.

- With a 4 stroke engine a full load cycle is once every 720° crankshaft

- $10^7$ cycles would occur after 166 hours running at a rated speed of 2000 rev/min.

- Operation for 1000 hours would give the following load cycles

# 1000 hour test cycles, material strength based

| | | |
|---|---|---|
| 4 | x $10^7$ | Full speed and load |
| 4 | x $10^6$ | Idle |
| 1.6 | x $10^7$ | Maximum torque |
| 1.065 | x $10^7$ | Governor run out speed |

**A total of $5 \times 10^7$ Cycles**

This proposed test cycle and duration would demonstrate a high degree of confidence in the durability of the engine with respect to mechanical fatigue

# Thermal Stress

- The maximum thermal stress occurs when a component is operated over the maximum temperature range normally encountered for an extended time
- On an engine this can occur when operating from full load to idle
- The maximum induced stress in thermaly loaded components is significantly higher than the maximum mechanically imposed stresses and thus the number of cycles to failure is lower than the endurance limit

# Cylinder head gasket durability

- The engine is cycled between full load and idle. During the idle mode cold coolant is passed through the engine
- Maximum component in service thermal stress is applied in the minimum time .
- The cylinder head gasket is in fact loaded beyond normal service conditions, due to differential expansion between the cylinder head, crankcase fixing bolts and gasket

# Design Validation Tests

- **Rapid Warm Up**
- The coolant and oil passage ways are fully instrumented and the rate of temperature rise noted.
- Objective, to ensure that the engine reaches operating temperature in the minimum time.
- This is becoming more important with new emission legislation

# Design Validation Tests

- Valve temperature survey
- Why ~ To ensure that valve heads and valve seats do not exceed the designed temperature limits under operating conditions
- How ~ Engine run at maximum speed and load for 2 hours. Temperature fusible plugs are fitted under the valve seat inserts, and valves of a specific material that changes hardness with temperature rise

# Design Validation Tests

- Piston Slack fit
- Why ~ To investigate fatigue of piston skirt and gudgeon pin boss
- How ~ The engine is assembled with increased piston to bore clearance 100 +- 10$U_m$ The engine is run for 180 hours at WOT maximum power rev/min

# Design Validation Tests

- **Piston Scuff <> Cold Test**
- Why ~ To establish piston cylinder bore and piston ring compatibility under cold starting conditions
- How ~ The engine is pre-cooled for 18 hours prior to test. Six starts are completed at $5^{\circ}$ C and six tests are completed at - $25^{\circ}$ C

# Design Validation Tests

- **Piston Scuff <> Hot Test**
- Why ~ To confirm piston to bore manufacturing tolerances
- How ~ The engine is run at maximum speed and load. The oil temperature is increased every 10 minutes by 5° C steps until 3.5 hours running completed or the engine has seized up

# Design Validation Tests

- **Piston Burn**
- Why ~ To determine the operating envelope within which the engine may safely operate
- How ~ This is a 100 hour test. The in cylinder temperature is monitored and the ignition/injection advanced to onset of rapid temperature rise. The condition has to be evaluated for many speeds and loads to build up a safety operating zone

# Design Validation Tests

- **Critical speed**
- Why ~ To ensure that the engine and auxiliary components do not fail when subjected to continuous running at critical speeds
- How ~ The engine is run at $10^7$ at a predetermined critical speed. There are normally high speed low amplitude and low speed high amplitude critical conditions

# Design Validation Tests

- **Valve seat wear**
- Why ~ To identify potential valve wear problems
- How ~ A three stage test.
  - 100 hours at 60% maximum power rev/min.Maximum rated power.
  - 100 hours at 60% maximum power rev/min. intermediate load.
  - 100 hours at maximum torque rev/min. at maximum torque

# Design Validation Tests

- **Exhaust manifold crack**
- Why ~ To determine the crack resistant qualities of exhaust manifolds and the torque retention properties of exhaust manifold fixing bolts.
- How ~ 200 hour test wherein the engine is run at maximum torque rev/min for 6 minutes, then idled for 4 minutes with maximum spot air cooling to the manifold

# Design Validation Tests

- **Thermal shock**
- Why ~ To ensure that prototype and production cylinder head gaskets operate satisfactorily when subjected to thermal cycling. To ensure that the bore and cylinder head distortion are held to design limits when subjected to thermal cycling
- How ~ 150 hour test. Engine cycled from full load/speed to idle with temperature delta of 75° C

# Design Validation Tests

- Thermal **shock continued**
- In these tests, the engine is cycled between full load and idle. During the idle mode, cold coolant/cold air is passed through the engine to rapidly reduce the component temperature. Maximum component in service thermal stress is thus applied in the minimum time. The cylinder head gasket is loaded beyond normal conditions due to the forces of differential expansion. Typically 2000 cycles are run.

# Design Validation Tests

- **Mixed Cycle**
- Why ~ To increase confidence level that prototype and production engines with all ancillaries will operate reliably for a design life
- How ~ 200 hours full load mixed speed. followed by 200 hours mixed load and speed. The number of repeat tests being dependant upon the degree of confidence in the reliability required.

# Design Validation Tests

- **General usage**
- Why ~ To gain an overall evaluation of the engine and component performance
- How ~ Typically an 8 stage test running from idle to maximum speed and load. [ Refer to mechanical failure slide ]  Each test is normally two tests of 200 hours followed by two tests of 800 hours.  N B Failure frequently occur in the first 100 to 200 hours [ B10%]

# Design Validation Tests

- **Full Load**
- Why ~ To ensure that assembly will operate reliably for a adequate service life
- How ~ The engine is cycled between maximum speed and power up to 500 rev/min over-speed. Typical test duration is 250 hours

# Design Validation Tests

- **So what constitutes a good result ?**
- No critical failure should occur
- Performance loss to be less than 5%
- Oil consumption within design limits
- Blow by should show no increase
- Minimal wear on major parts
- Components to be in good condition
- Specific fuel consumption not to increase by more than 5%

# What constitutes a good test result

At completion, the engine should be in a good condition and perform as specified

No critical failure should occur in the test

Performance loss to be less than 5%

Oil consumption within design targets

Blow-by should show no increase

Minimal wear on major parts

Good component condition

Specific fuel consumption should not increase by more than 5%

# Design Validation Tests and the Development Engineer

- What does design validation testing give the engineer
- A means of comparing differing engine build specifications , one with another
- An aid to engine development from design level one to production sign off
- A production quality tool

# BASIC MEASUREMENTS

## Engine Instrumentation

- Air cleaner differential pressure
- Boost ( if applicable) centre of inlet manifold
- EGR Vacuum/pressure
- EBP 75mm+/-10mm down stream of mating flange
- Fuel supply pressure, +ve.. : -ve..
- Intake manifold vacuum centre of manifold
- Oil Pressure ; Engine gallery take off position
- Temperature Thermocouples always as close to outlet/inlet as possible in a position where flow is unrestricted
- Fuel temperature, measure as close to the measuring head as possible

# BASIC MEASUREMENTS

## Engine Instrumentation

- <u>ACCURACY</u>
- Fuel flow +/-1% of reading
- Pressure +/- 0.5% of full scale
- Speed +/- 5 rev/min throughout range
- Injection/spark +/- 0.5° of reading
- Temperature +/- 1.5 °C up to 150°C
- Temperature +/- 3.5°C between 150° and 1000°
- Torque +/- 0.5Nm or +/-1% of full scale
- Emissions +/- 3% of full scale

# BASIC REQUIREMENTS

## CALIBRATION

Instruments and test equipment must be calibrated at test facility specified calibration intervals and must have current laboratory calibration records.

Full tractability of all calibration records is a prerequisite of all professional engine test laboratories

# WHAT READING ARE IMPORTANT

## PRESENTATION OF DATA

Data to be plotted against engine speed

- Corrected B.M.E.P. - kPa ( psi)
- Corrected Torque - Nm ( lb-ft)
- Corrected Power - kW ( BHP)
- Fuel Flow - kg/hr ( Lb./hr)
- SFC - g/kW-hr ( Lb./HP-hr)
- Spark Advance/Injection point ° crankshaft
- Intake manifold vacuum - kPa ( in. Hg)
- Exhaust back pressure - kPa (in.Hg)
- CO% (etc) at exhaust manifold flange

# Design Validation Tests

- **TAKING READINGS**
- Allow engine to stabilise at each set point
- Oil and coolant temperatures to be held constant to pre-determined limits
- Allow a minimum of 5 minutes between each set of readings
- Instigate fuel and emission readings at the end of the stabilisation period

# CONFIDENCE

- **NEED TO REPEAT ALL ENGINE TESTS**
- In order to have statistical confidence in the results of any performance test, it is necessary to the repeat the test at least twice, if possible three times.

# DESIGN LEVEL ONE STANDARD DVT TESTS

- Full load cycle test
- Thermal shock test
- Exhaust manifold crack tests
- Valve wear cycle tests
- General usage cycle test
- Critical speed tests

# DESIGN LEVEL TWO STANDARD DVT TESTS

TESTS AS PER DESIGN LEVEL ONE

- THE NUMBER OF TESTS AND THE DURATION OF EACH TEST INCREASED.
- IN FIELD DURABILITY TESTS START

# OFF TOOL VALIDATION COST SAVINGS

- Intelligent interpretation of tests
- Ensure that all tests produced to the highest standards
- Produce significant savings in the period between design concept and production sign off

# VALUE FOR MONEY

To achieve the maximum value from any DVT work, the measurement and assessment of critical components pre and post test is a prerequisite.

This assessment would include the measurement of wear, rating of component condition and analysis of fluids and lubricant.

This data enables the engineer to undertake predictive analysis of wear rates [ Re Bath Tub !] and thus to increase his confidence level in the validity of the test results and thus reduce the total number of tests to be undertaken

# OIL ANALYSIS

- To gain information with regard to the integrity of the engine under test, it is recommend that 125 cc samples of engine oil are taken at agreed intervals and the following analysis performed :

- Fuel Dilution — Reference ASTM D 3524
- Soot Content — Reference IFP 303/03
- Viscosity — Reference ASTM D 445 (N40° C 100° C)
- Metal Content — Reference ASTM D 4951/5185
- Sulphur Content — Reference IP 244/ICP
- Base No. (Acidity) — Reference ASTM D 664/2896.

# Engine Application

- Objective is to establish the probability of a given product reaching its design life which in turn may be dictated by legislation
- Bench tests must replicate and accelerate in service life conditions
- A typical representative test cycle for all engine applications is not possible
- Specialist tests have been developed to test engines over the 4 most important operating conditions

# WHAT NOW !!

- We understand why we have to test, but prior to discussing types of tests, let us for a moment consider how one can get the maximum value out of each test

# Your place in the equation

- The importance of the technicians place within the automotive industry cannot be too highly stressed.
- It is the fine attention too detail that makes the difference between a successful new model and a dead duck.
- **How can this be ?**

# The consequence of poor attention to detail

- Imagine if you will this scenario
- A Saudi Prince has ordered a series of Vehicles ~ he tells his chums at the oasis and the Polo Club
- The vehicles are delivered
- The Prince shows them to his chums, who point out the oil leaks. The leaks were noticed on test but not reported !!
- The Prince has lost face ~ The company has lost many potential sales

# Close attention to detail the 'Professional Technician'

- The same scenario
- There were oil leaks on test, but these were noted and the company were able to rectify prior to production sign off
- The Prince receives the units
- He show it to his chums, NO OIL LEAKS
- They are impressed
- Additional sales are made
- A simplistic story BUT valid

# Your responsibility

- Accuracy and Attention to detail must become a way of life for you
- You are a professional and are on the ladder to becoming a chartered engineer
- You must do all in your power to ensure that the results you produce are correct ~ this is not as simple as it sounds